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U-TUBE AERATION

Rex C. Mitchell

Rockwell International Corporation

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Environmental Protection Agency

September 1973

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Mass transfer and fluid dynamics correlations, plus a design computer program, were developed for use in designing U-tube systems. A satisfactory basis for design now exists, although additional improvements are needed.

~~[illegible]~~ U-tube systems are a practical, flexible, efficient method for aeration for a number of applications. They are well-suited to applications in which it is desired to raise the oxygen concentration of a moving stream, even to saturation. ~~(Mitchell-Rocketdyne)~~ (EPA)

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September 1973

U-TUBE AERATION

by

Rex C. Mitchell

Project No. 17050 DVT
Contract No. 68-01-0120
Program Element 1B2043

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ABSTRACT

The results of two experimental and analytical projects to develop and evaluate the U-tube aeration concept are presented. Experimental data were obtained to characterize the mass transfer and fluid dynamics behavior of U-tube systems over large ranges of design variables and operating conditions. Tests were made first with a pilot-scale (2-inch-diameter) U-tube. Subsequently, full-scale (8- to 20-inch-diameter) prototype systems were successfully designed, constructed (under EPA grant projects), and operated in sanitary sewer systems in Jefferson Parish, Louisiana, and Port Arthur, Texas. These field installations have been effective in reducing previous serious odor and corrosion problems resulting from sulfides. No maintenance has been required on aspirated-air systems in approximately 2 years of continuous operation.

Mass transfer and fluid dynamic correlations, plus a design computer program, were developed to use in designing U-tube systems. A satisfactory basis for design now exists, although additional improvements are needed.

It was found that U-tube systems are a practical, flexible, efficient method for aeration in a number of applications. They are well-suited to applications in which it is desired to raise the oxygen concentration of a moving stream, even to saturation.

This report was submitted by the Rocketdyne Division of Rockwell International, Canoga Park, California, in fulfillment of Project No. 17050 DVT, Contract 68-01-0120, and incorporates the results from Contract 14-12-434, under the sponsorship of the Environmental Protection Agency. The technical work was completed in October 1972.

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SECTION I

CONCLUSIONS

1. A U-tube system is a practical, flexible, efficient method for aeration for a number of applications.

2. U-tubes generally are not suitable or competitive in applications requiring large additions of oxygen (e.g., in activated sludge treatment). They are better suited to applications in which it is desired to raise the oxygen concentration of a moving stream, even to saturation (e.g., postaeration of treated effluent, aeration for fish hatcheries, and *in situ* aeration of sanitary sewers).

3. There is ample flexibility in the choice of U-tube configurations plus other design variables to permit efficient specific designs in a variety of applications and for different requirements.

4. U-tube aeration systems require little space, can be designed with no moving parts, require no operating labor and little maintenance, and can (for suitable application) result in substantial cost savings over other aeration methods.

5. A satisfactory basis for designing U-tube systems now exists, although additional improvements are needed.

6. Actual full-scale installations have been successfully designed, constructed, and operated in sanitary sewer systems in Louisiana and Texas. Six U-tube systems of two major types in four locations with pipe diameters from 8 to 20 inches have been effective in reducing previous serious odor and corrosion problems resulting from sulfides. No maintenance has been required in approximately 2 years of continuous operation for aspirated-air systems.

7. Deep U-tube systems can be installed without complications, even in relatively unstable soil and with a high ground water level.

SECTION II

RECOMMENDATIONS

It is recommended that U-tube aerators be considered for any application that requires raising the dissolved oxygen level of a flowing water or wastewater stream. The correlations and design techniques described in this report can be used for parametric predesign studies in preparation for economic evaluations of alternative aeration methods; they also can be used to establish design points and conditions in those cases where U-tube systems are selected.

Although the design techniques given in this report are recommended as the best available basis for making design calculations, improvement is needed in the predictive bases for some elements of a U-tube system. There is a particular need to improve the aspirator designs and design correlations which have been used up to this time. Further consideration also should be given to the use of oxygen in U-tubes. It will be important in such cases to provide adequate depth and residence time to ensure high oxygen utilization efficiencies.

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SECTION III

INTRODUCTION

There are many requirements for aerating water and a variety of techniques that can be used to accomplish this. The U-tube concept is an interesting and not widely known aeration method. This type of aeration system is simple in concept, basically consisting of two elements: (1) a device for entraining air (or oxygen) into a flowing water stream (e.g., an aspirator device or a compressor introducing air through a diffuser), followed by (2) a vertical U-shaped flow path to provide residence time in a zone of above-atmospheric pressure during which oxygen absorption from the entrained air takes place with a very favorable driving force. The U-shaped flow path can take various forms (e.g., a pair of vertical pipes connected by a 180-degree return bend at the bottom, or a pair of concentric pipes with flow downward through one passage and upward through the other).

The label "U-tube" apparently was first used in the literature by Bruijn and Tuinzaad (Ref. 1) in 1958, although the original aeration experiment they describe (using an aspirator-air U-tube) was conducted by the Dutch Research Institute K.I.W.A. Related aeration systems were considered approximately 40 years ago (Ref. 2). Rocketdyne has been studying and developing this aeration technique in various forms, first under internal funding (Ref. 3) and later under EPA sponsorship as described in this report and Ref. 4 and 5. Speece and other researchers have reported their work with U-tube aeration systems, primarily using compressed air injection (Ref. 6 and 7).

A 15-month experimental and analytical effort, initiated in June 1968 under EPA Contract No. 14-12-434, was conducted by Rocketdyne to investigate and begin development of the U-tube aeration concept for various wastewater applications (Ref. 4). Three major tasks were accomplished: (1) experimental verification of oxygen transfer efficiencies and exploration of practical aspects of U-tube operation; (2) analytical investigation of two major applications--postaeration of effluent from a sewage treatment plant and *in situ* aeration of sanitary sewer flows to prevent anaerobic conditions; (3) investigation and design of full-scale prototype U-tube systems, with particular emphasis on designs for installation in the Jefferson Parish, Louisiana, sewer system. Assistance was also given to the EPA in the design of U-tube systems for installation in the sewer system at Port Arthur, Texas.

These full-scale prototype U-tube systems were installed in Jefferson Parish and Port Arthur under EPA Grants 11010 ELP and 11010 DYO, respectively. Subsequently, under EPA Contract No. 68-01-0120 (initiated in June 1971), Rocketdyne provided technical direction for field evaluation tests of these systems and used the data to improve the design bases previously developed. This report describes the results of both projects (EPA Contracts 14-12-434 and 68-01-0120).

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There was an evolutionary process during the two projects, spanning a period of about 4 years, with respect to the various steps of experimental testing, data analysis, design, further testing, etc. A flexible pilot-scale U-tube system was designed originally, based on the limited information available in Ref. 1. Data from tests with this pilot-scale system were used to develop pressure drop and mass transfer correlations and an initial design computer program. This program was used in selecting design conditions for the full-scale U-tube systems that were constructed in Jefferson Parish and Port Arthur. The data from field tests with these systems were then used, together with the pilot-scale data, to develop improved correlations which were combined into an improved U-tube design program. Descriptions of the experimental tests, data analysis, correlations, design techniques, and conclusions are given in this report.

SECTION IV

EXPERIMENTAL STUDIES

AERATION STUDIES

Basic experiments with deoxygenated tap water were conducted in a pilot scale (2-inch diameter) U-tube aerator. Four hundred ten (410) test runs were made over a 4-month period. Data relevant to oxygen transfer and pressure loss were obtained as functions of U-tube depth, water velocity, air-to-water ratio, and air aspirator configuration. Five U-tube depths were investigated, ranging from 9 to 45 feet. Head loss through the system varied from 1 to 8 feet. Superficial water velocity (i.e., velocity of water if no air were present) varied from 1.4 to 3.4 ft/sec with a few runs above and below this range. The air-to-water volume ratio was varied from zero to approximately 0.2. Two air aspirator designs were investigated. Runs 1 through 94 were made with a tapered center-plug aspirator configuration. When it became apparent that permanent pressure losses across this device were excessive, a second aspirator was constructed; runs 95 through 410 were made with this venturi aspirator. Performance in terms of pressure loss was markedly better for the venturi design.

Apparatus

The pilot scale U-tube aerator was located in the Igniter Development Area (IDA) of Rocketdyne's Santa Susana Field Laboratory. The tube was suspended from the 50-foot platform of an existing steel tower, with associated tanks and instrumentation mounted on the platform. A schematic diagram of the experimental system is shown in Fig. 1.

The U-tube was constructed of 2-inch diameter pipe and hose. The down-leg contained a ten-foot section of glass pipe located just below the aspirator exit. The remainder of the U-tube consisted of 8 to 10-foot sections of 2-inch PVC pipe joined with threaded unions. This segmented construction made it easy to change depth. A section of 2-inch steel-reinforced rubber hose was installed in the top portion of the up-leg to make it possible to vary the head loss across the system by moving the adjustable height bracket. The auxiliary plumbing shown in Fig. 1 was fabricated primarily of stainless steel tubing. The return bend initially used was a 2-inch diameter glass section (made by Kimble Glass Co.) with pipe thread end adaptors. During the program a change-over was made to a return bend of two 90-degree elbows and a short pipe nipple. This change was due to difficulty in aligning the legs of the U-tube at the shorter lengths with the glass return bend.

The deaeration, surge, and U-tube tanks had approximate capacities of 100, 50, and 31 gallons, respectively. The deaerator feed pump was a 1/2-hp centrifugal pump rated for approximately 50 gpm at 40 feet of

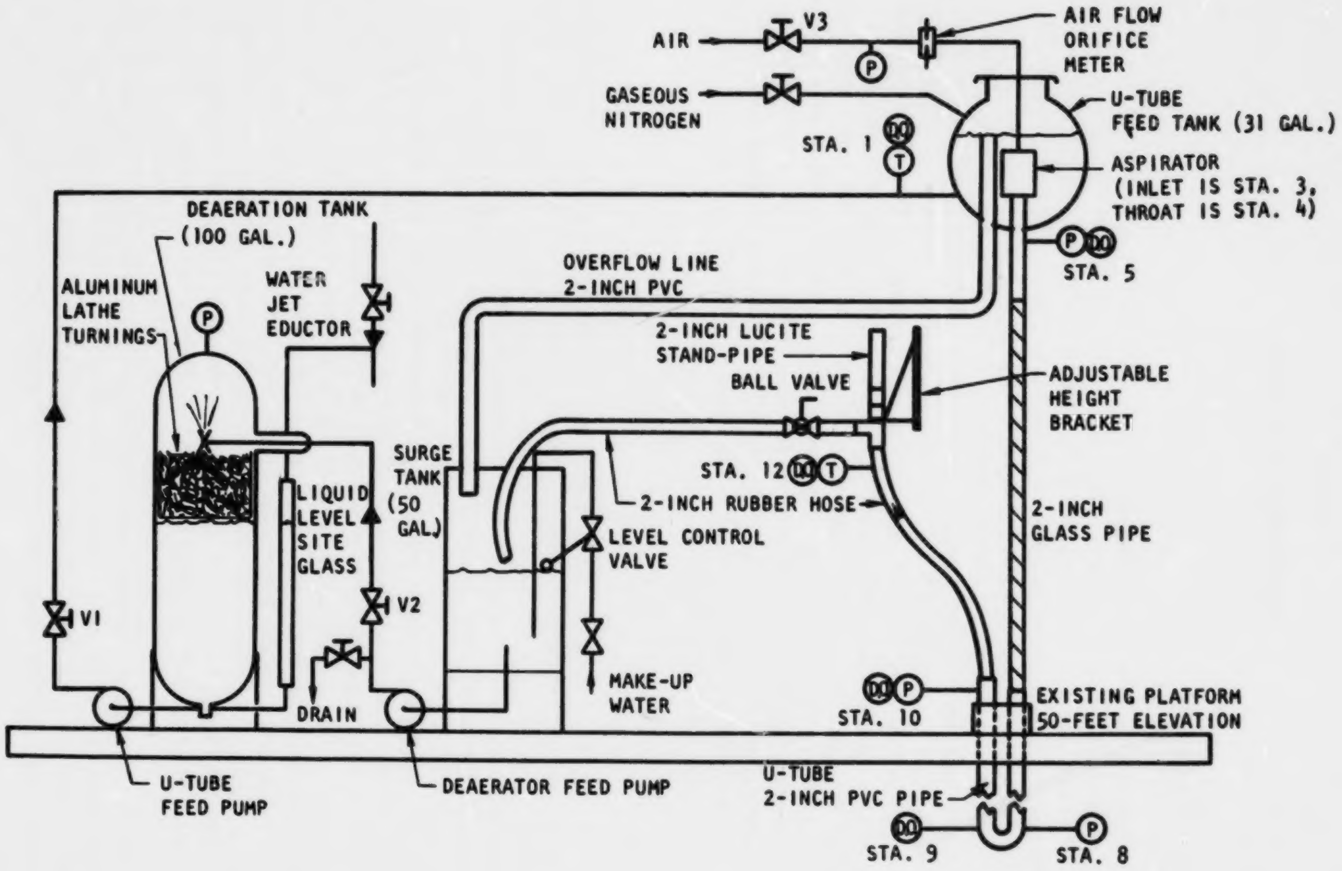

AIR
V3
AIR FLOW
ORIFICE
METER
GASEOUS
NITROGEN
P
U-TUBE
FEED TANK (31 GAL.)
STA. 1
DO
T
ASPIRATOR
(INLET IS STA. 3,
THROAT IS STA. 4)
P
DO
STA. 5
DEAERATION TANK
(100 GAL.)
ALUMINUM
LATHE
TURNINGS
P
WATER
JET
EDUCTOR
OVERFLOW LINE
2-INCH PVC
2-INCH LUCITE
STAND-PIPE
BALL VALVE
ADJUSTABLE
HEIGHT
BRACKET
SURGE
TANK
(50
GAL.)
STA. 12
DO
T
2-INCH RUBBER HOSE
2-INCH
GLASS PIPE
LIQUID
LEVEL
SITE
GLASS
LEVEL CONTROL
VALVE
V1
V2
MAKE-UP
WATER
DRAIN
DO
P
STA. 10
EXISTING PLATFORM
50-FEET ELEVATION
U-TUBE
FEED PUMP
DEAERATOR FEED PUMP
U-TUBE
2-INCH PVC PIPE
DO
STA. 9
P
STA. 8

Figure 1. Schematic Diagram of U-Tube Experimental Apparatus

discharge head. The U-tube feed pump was a 5-hp centrifugal pump rated for 160 gpm at 70 feet of head. Gate valves were used for water flow control.

The center-plug aspirator consisted of a hollow, tapered aluminum plug which was set in a cone attached to the entrance of the U-tube (Fig. 2). Six sets of radial holes were placed at different diameters in the plug, and all or part of the holes could be used as desired (normally, one to three rows of holes were used; the others were closed). The constricted annular flow area at the U-tube entrance (between the plug and the 2.067-inch inside diameter of the pipe) caused accelerated water velocity and reduced pressure, resulting in aspiration of air through the plug holes into the water stream. A pipe attached to the core of the plug was connected to the air flow orifice meter. By raising and lowering the plug, variable annular areas (contraction ratios) were attained. Initially, the plug was used without a flow collimating cone. The cone was added when it became apparent that for efficient aspiration, the water flow had to be aligned somewhat parallel to the plug surface.

The second aspirator used was basically a Herschel-type venturi with inlet and exit full-cone angles of 21 and 7 degrees, respectively. Figure 3 is the venturi construction drawing. The unit was machined from 6061 aluminum. The venturi had a contraction area ratio of 8 based on the full flow area of 2-inch PVC pipe (2.067-inch I.D.). Entrance pressure loss was minimized by designing for low entering water velocity (i.e., providing a large diameter entrance). A threaded section on the diffuser cone enabled the unit to be screwed into the bottom of the feed tank. Air was manifolded into 4 ports at the throat (Fig. 4). A pipe attached to the manifold was connected to the air flow orifice meter. A lucite orifice meter was constructed and calibrated for measuring air flow. The differential pressure across the orifice was measured with an inclined water manometer.

Three Beckman Dissolved Oxygen Analyzers were used for monitoring dissolved oxygen--two Model 778 process analyzers and one Model 777 laboratory analyzer. Two permanent probes were placed at Stations 1 and 12 (see Fig. 1) for monitoring inlet and outlet dissolved oxygen. The third probe was used for making intermediate D.O. measurements at Stations 5, 9, or 10 (as shown in Fig. 1). Calibrations were made at the beginning and at the end of each day's testing.

Intermediate pressure loss measurements were made at three stations: 5, 8, and 10. Pressures at these stations were measured by use of water manometers constructed of 1/4-inch tubing, with the top 5 to 7 feet made of Tygon (clear plastic tubing) so that the liquid level could be observed. Short U-shaped sections of tubing were placed next to the pressure taps to prevent air bubbles from entering the manometer lines (they were very effective). In some cases, short beds of coarse metal turnings were also placed in the lines to dampen pressure fluctuations. The differential height between the feed tank liquid level and the level in the

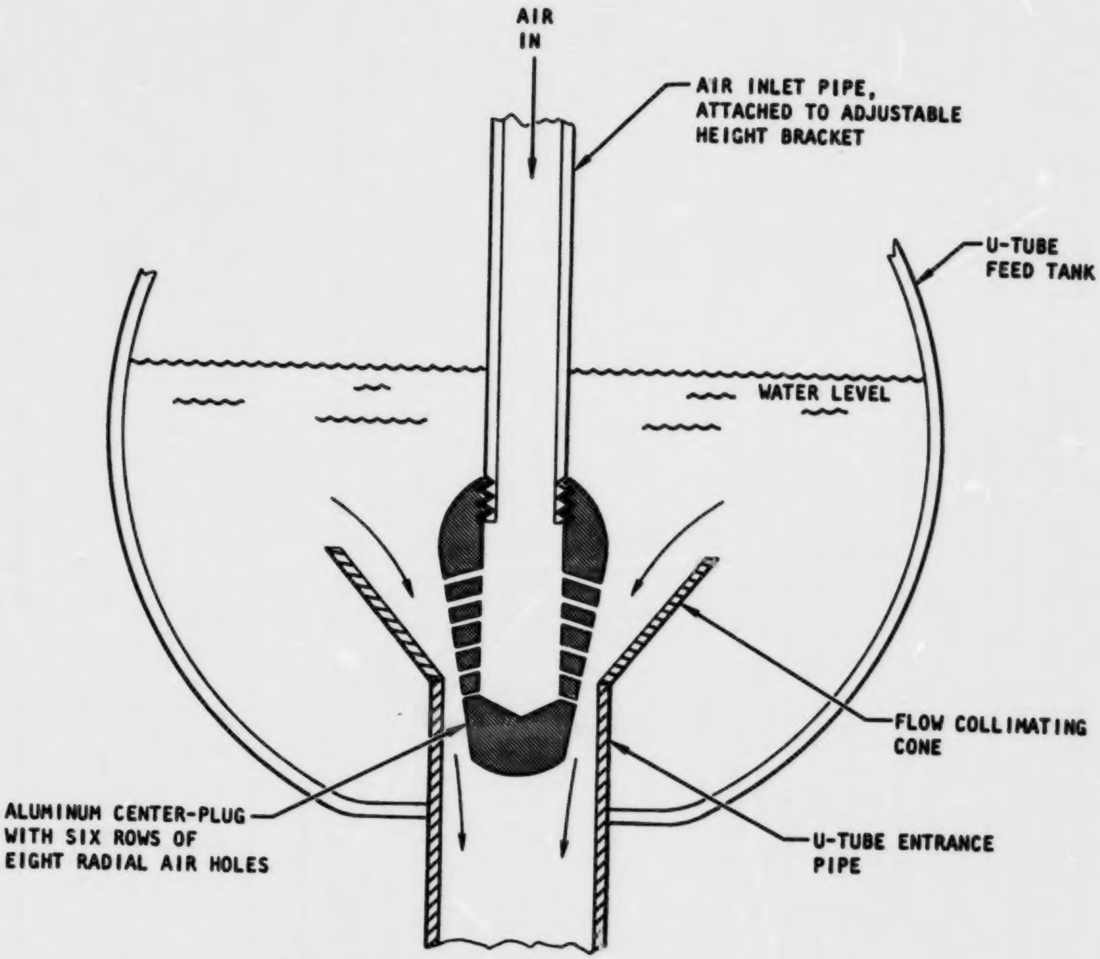
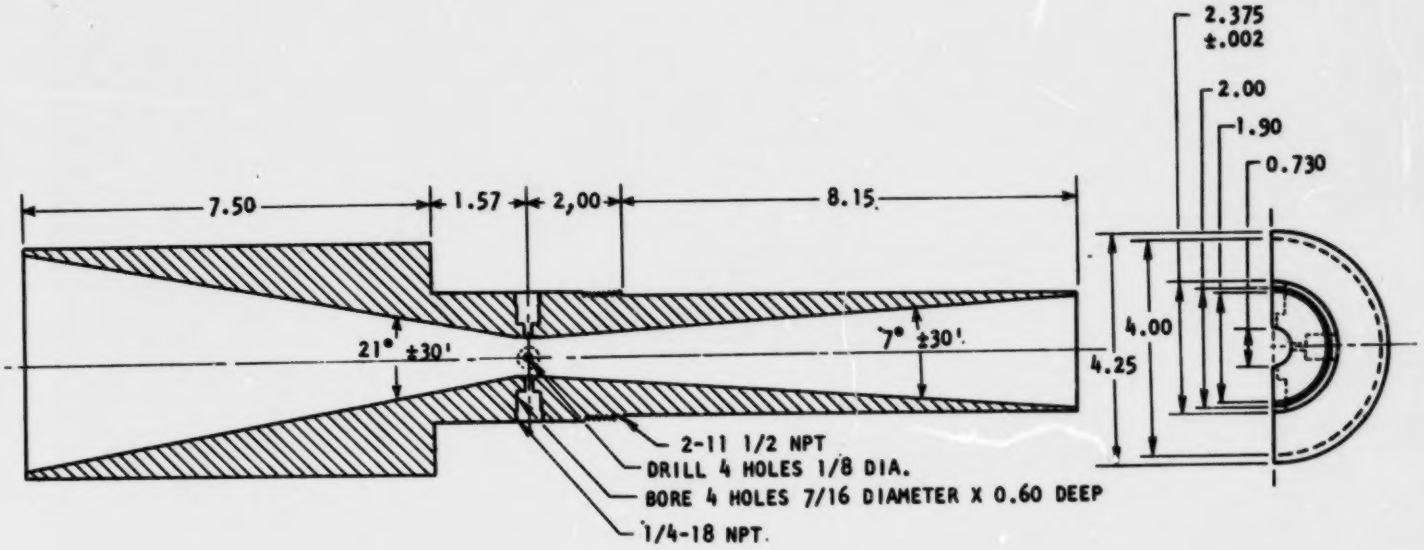

AIR
IN
AIR INLET PIPE, ATTACHED TO ADJUSTABLE HEIGHT BRACKET
U-TUBE FEED TANK
WATER LEVEL
FLOW COLLIMATING CONE
ALUMINUM CENTER-PLUG WITH SIX ROWS OF EIGHT RADIAL AIR HOLES
U-TUBE ENTRANCE PIPE

Figure 2. Center-Plug Aspirator


2.375
±.002
2.00
1.90
0.730
7.50
1.57
2,00
8.15
21° ±30'
7° ±30'
4.00
4.25
2-11 1/2 NPT
DRILL 4 HOLES 1/8 DIA.
BORE 4 HOLES 7/16 DIAMETER X 0.60 DEEP
1/4-18 NPT.

NOTE:

1. ALL DIMENSIONS ARE ±.01 IN. UNLESS OTHERWISE SPECIFIED
2. THROAT TO BE 0.50 LONG
3. 2-INCH PIPE THREADS TO BE 1 1/4 LONG
4. 1/4-INCH PIPE THREADS TO BE 3/8 DEEP

Figure 3. Venturi Aspirator Design

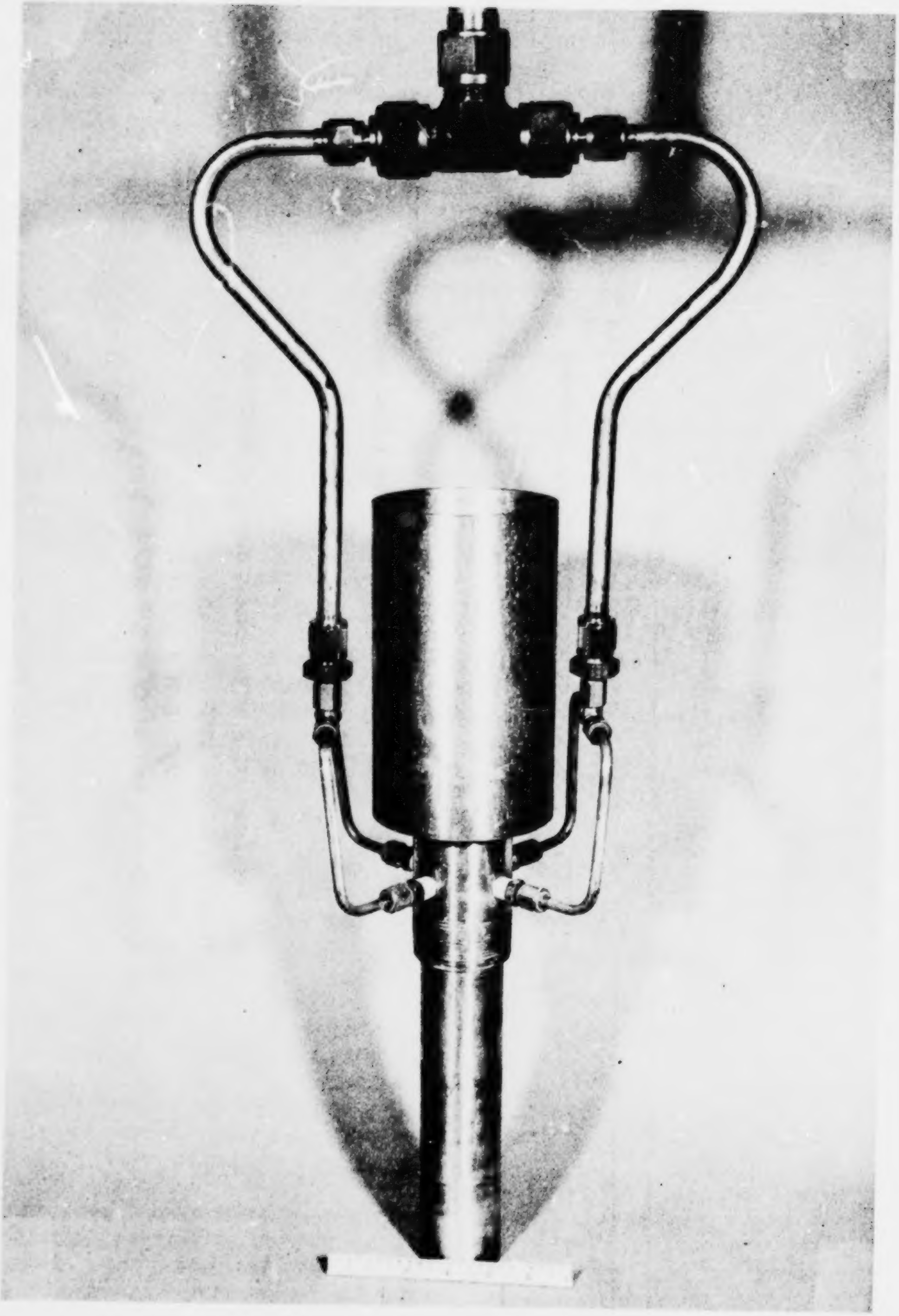


Figure 4. Venturi Aspirator Assembly with Inlet Air Manifold (Scale is in inches)

water columns represented the pressure loss to the various stations. The lucite standpipe, ball valve, thermometer and dissolved oxygen probe, shown at the exit of the U-tube in Fig. 1, were attached to the adjustable height bracket.

A laboratory investigation was conducted to develop techniques for measuring dissolved oxygen concentration in the water (which also contains entrained air) flowing through the U-tube experimental system. It was judged that rapid in-line measurements would be more efficient from experimental operating considerations and would avoid the difficulties with sampling and de-entrainment of the undissolved gases for a sampling-chemical analysis method. After various laboratory tests it was found that very satisfactory D.O. measurements could be made in a two-phase air-water flowing stream with a Beckman polarographic probe if the probe axis was oriented approximately 30 to 60 degrees downstream from a position perpendicular to the pipe's centerline axis. With such an orientation, the problems with impingement and attachment of air bubbles are eliminated. It was also found, with the probes and instruments used in this study, that a stream velocity as low as 1.0 ft/sec was sufficient to ensure accurate, stable D.O. readings which were independent of flow velocity (the manufacturer's literature recommends a more conservative value of 1.8 ft/sec). The assemblies for installing the D.O. probes into the experimental U-tube system piping consisted of a standard Beckman sealed gland assembly which was slightly modified and welded into a 4-inch long pipe nipple at a 45-degree angle. This nipple adapted to 2-inch PVC pipe fittings, thus functioning as a 45-degree tee. The D.O. probe was installed in the sealed gland assembly in such a way that the probe axis was oriented approximately 45-degrees downstream from a position perpendicular to the pipe center line, and with the probe face extending about 1/2-inch from the pipe wall into the flowing stream.

Facility Operation

Operation of the system was as follows: Make-up tap water was introduced into the surge tank through the liquid level control valve. Water was pumped into the deaeration tank where dissolved gases were removed under vacuum. The deaerator was evacuated to a vacuum greater than 25 inches Hg by a Penberthy water jet eductor, which was connected to the ullage space above the packed bed. Water entered the deaerator through solid cone spray nozzles and was allowed to trickle over a bed of aluminum lathe turnings in the tank ullage. The deaerated water was then pumped up to the U-tube feed tank where a fraction of the water overflowed to the surge tank while the bulk of the flow entered the U-tube. The overflow allowed control of a constant liquid head above the aspirator, which could be varied by changing the length of the overflow pipe in the feed tank. Water leaving the U-tube entered a tee attached to the adjustable height bracket (Fig. 1). A 2-inch diameter lucite standpipe screwed into the run of the tee acted as a vacuum break for the system. The water then returned to the surge tank.

The vertical distance between the water level in the feed tank and the water level in the lucite standpipe established the head loss (ΔH) across the system.

Once the tanks were brought to their operating levels and the U-tube was full, all water was recycled. Water in the surge and dearation tanks was held at each desired steady-state level by throttling the pump discharge valves (V1 and V2 in Fig. 1).

Experimental Procedures

A typical test run commenced by setting the approximate desired ΔH across the U-tube. System ΔH was set by varying the level of the adjustable height bracket at Station 12. The dissolved oxygen probes were then calibrated in air to 100 percent saturation and placed in their adaptor gland assemblies. With the tapered plug aspirator, a contraction ratio was selected and then set by backing the plug a predetermined vertical distance away from its seated position (seating the plug closed the U-tube entrance). No adjustment was necessary with the venturi aspirator. With the air inlet valve (V3) closed, the pumps were started. Liquid levels in the deaeration and surge tanks were set, and the water jet eductor was turned on. The system was allowed to run until the deaerator reached a steady-state pressure and the inlet and outlet dissolved oxygen meters gave identical readings.

After attaining steady-state operation with only water flowing, the air inlet valve was opened. At a given air flowrate, water flowrate measurements were made by diverting the return to the surge tank into a 5-gallon container and measuring the time to fill with a stopwatch. Four measurements were made for each run to ensure steady-state operation and a reliable average flowrate. Initially, an orifice flowmeter was placed in the return line to the surge tank for determination of water flow. The orifice gave oscillating differential pressure readings, added to the system ΔH (causing overflow in the lucite standpipe at certain ΔH settings), and hindered the flexibility of the ΔH setting. The orifice plate was removed in favor of a bucket and stopwatch measurement technique before the start of experimentation. For Runs 1 through 25, water flowrate was allowed to vary randomly at a given air setting. After Run 25 the air flow, the plug setting, and/or the system ΔH were generally set so that the water flowrate obtained was 15, 20, 25, 30 or 35 gpm plus or minus 1 gpm. After steady-state conditions were obtained, dissolved oxygen measurements, pressure losses, ΔH setting, plug aspirator setting, air and water flowrates, and water temperature were recorded.

The next run was made by either adjusting the air throttle valve, adjusting the plug setting, and/or resetting the ΔH across the system (all while the pumps were running), and then following the same data acquisition procedures. In this way a series of water flowrate vs air-to-water ratio measurements was made as a function of system ΔH or plug setting for each U-tube length. At each new U-tube length a series of single-phase (no air) runs was made to characterize the system pressure drop in terms of water flow only.

System Operating Behavior

The performance of the U-tube is directly related to the phenomenon of vertical, gas-liquid two-phase flow. Such effects as start-up instability, oscillating flows, regime shifts, up-leg pressure recovery, and trade-off of air-water flowrate vs pressure loss were important to the experimentation. Because the explanation of these effects is based on two-phase flow phenomena, a short, qualitative description of the field is in order.

Two-phase vertical flow is characterized by a series of regimes or patterns which are dependent on air-to-water ratio, water flowrate, and pipe diameter. A visual summary of these regimes is sketched in Fig. 5, taken from a review paper by Anderson and Russell (Ref. 8). Steady-state U-tube operation is represented by the bubble flow regime, a continuous liquid phase with the gas homogeneously dispersed as bubbles. Anomalous flow behavior was usually due to approaching slug flow or the actual onset of slug flow. Froth, annular, and mist flow were not encountered in this investigation. The slug flow regime is visually characterized by consecutive passage of alternate slugs of liquid and bullet-shaped slugs of gas. In contrast to the other regimes, it is also characterized by varying pressure drops, i.e., pressure fluctuations at a fixed station in the system (Ref. 9).

The dependence of flow regime on air-to-water ratio is visually apparent from Fig. 5. The dependence on pipe diameter is more subtle. Although a precise quantitative equation for predicting the diameter functionality of the regimes is not available, a theoretical qualitative description can be made. For the slug flow regime it is apparent that the bullet-shaped slug takes on the approximate diameter of the pipe. Given the injection of 1/4-inch diameter bubbles into 1/2-inch diameter pipe, a slight degree of bubble coalescence could cause the formation of a bubble which has the cross-sectional area of the pipe. If this occurs, slug flow would result. Furthermore, a 1/2-inch diameter slug of gas is relatively stable hydrodynamically, i.e., the slug would tend to remain in the system. In the case of 1/2-inch diameter bubbles injected into a 2-foot diameter pipe, it is apparent that a great deal of coalescence would have to occur before a 2-foot diameter slug could form. Also, a 2-foot diameter slug of gas is much less stable hydrodynamically and, therefore, would probably break up.

The shear forces at the bubble-liquid interface are proportional to water flowrate. Higher bubble-liquid interfacial shear would imply greater interfacial turbulence and lead to bubble breakup. The implication is that higher water flowrates reduce the tendency toward slug

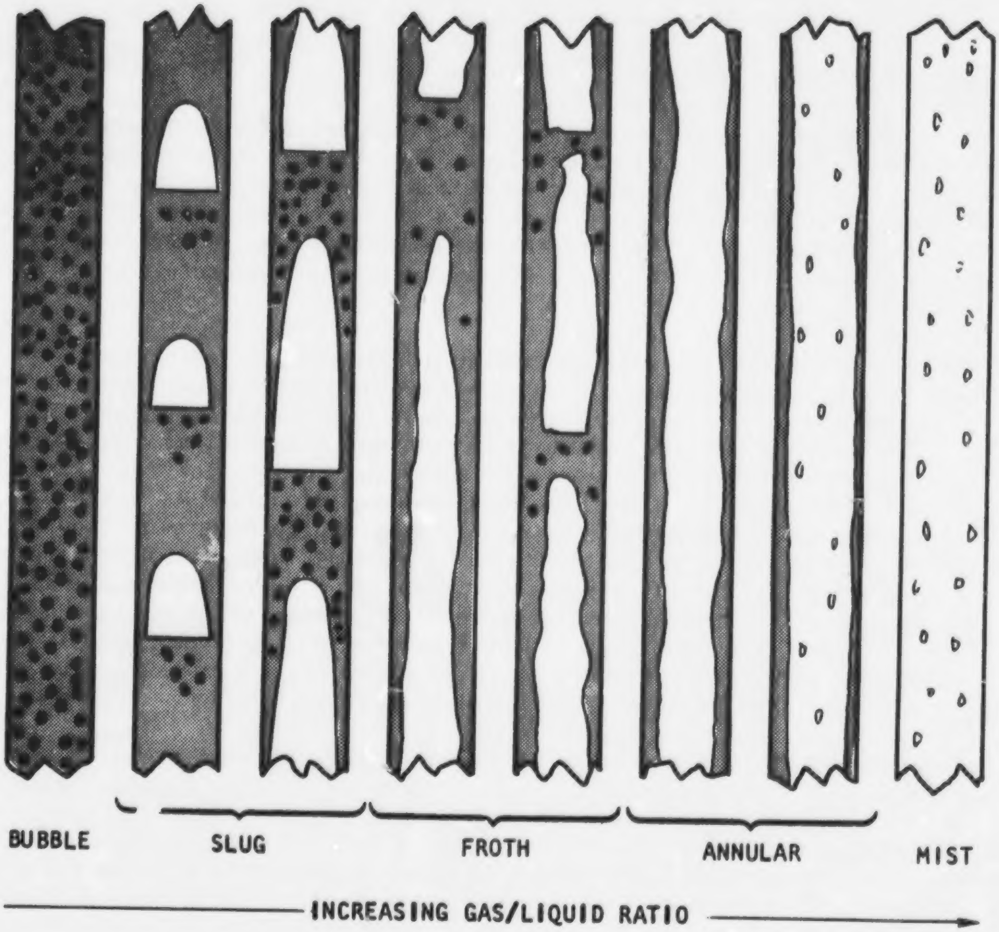

BUBBLE
SLUG
FROTH
ANNULAR
MIST
INCREASING GAS/LIQUID RATIO

Figure 5. Vertical Two-Phase Flow Patterns

flow at a given air-to-water ratio and pipe diameter. This trend is qualitatively substantiated by the observations of Griffith and Wallis, given in Ref. 8.

When starting the experimental U-tube, the ΔH across the system was set before the pumps were turned on. The initial down-leg liquid level was usually in the glass pipe, leaving several feet of air between the aspirator and the liquid surface. Upon start-up, this air was flushed out of the system in the form of long air cones (slug flow). Since no additional air was allowed into the system, the pressure loss across the cones was overcome by the system ΔH, and the U-tube was rapidly flushed of air. After measurement of the single-phase water flow, air was allowed to enter the system. To hold the same single-phase water flowrate after air introduction, the system ΔH had to be increased. With the addition of more air, the ΔH had to be increased further. This is reasonable with respect to the bubble flow regime depicted in Fig. 5. Although pressure loss was incurred in the down-leg, at high air-to-water ratios and/or low water flow rates, some net pressure recovery was observed in the up-leg. This is due to the air-lift effect counterbalancing the frictional losses.

During normal bubble flow operation, very slight (less than 1 percent) air flow and pressure loss oscillations were observed (with both aspirators). These oscillations did not impede data acquisition and were probably a result of the system design. At high air-to-water ratio, the oscillations increased to a noticeable level (perhaps 5 to 10 percent of the manometer reading). Observations showed the system to be still in the bubble flow regime, but with a time-dependent bubble density. In these cases, data acquisition was made by visual time averaging of pressure losses and air flows. Intermediate and outlet dissolved oxygen measurements generally showed only small oscillations (perhaps 2 percent of the reading) which were readily averaged Of course, the water flow measurement was averaged by the nature of the technique.

Increasing the air-to-water ratio to even higher levels resulted in a transition to true slug flow. At first, small air caps would form in the dense bubble zones. With additional air, these caps coalesced into bullet-shaped cones. Very large oscillations in pressure loss, air flow, dissolved oxygen, and water flow were apparent at this time. Net U-tube pressure loss would eventually overcome the system ΔH. The result was upward or reverse flow in the down-leg, due to the air-lift effect of the cones. Slug flow was easily avoided in actual operation. At the largest system ΔH (approximately 8 feet), the maximum air-to-water ratio at a given water flowrate was usually in the bubble flow regime. Slug flow was encountered only at extreme conditions and usually with long U-tubes where the time for slug coalescence was great.

AIR BUBBLE CHARACTERIZATION

High-speed motion pictures of the bubbles were taken in the glass section at the top of the down-leg and at the glass return bend for the 45-foot U-tube. The 45-foot depth was selected because this was the only length permitting convenient access to the return bend. For evaluating mass transfer coefficients, information was needed regarding bubble size, shape, and slip velocity distributions, plus the change in these with respect to depth, water flowrate, and air-to-water ratio.

Pictures were taken with two Milliken high-speed cameras at approximately 400 frames per second. The cameras were set up electrically in series at the top and bottom of the U-tube enabling simultaneous photography at the two stations. Segments of nine runs were photographed for each aspirator design. Runs were selected with six different water velocities over a range of air-to-water ratios for the center-plug aspirator. Three water velocities, but a larger range of air-to-water ratios were represented in the venturi aspirator system photographs. Data were taken from enlarged projections of the pictures. The bubbles measured were close to the center line of the glass pipe to minimize distortion of the bubble dimensions. Bubble dimensions were determined for each run at each station from a random sample of bubbles. Bubble velocities were readily determined from the film speed and the number of frames required for a bubble to transverse a section of the pipe between two marks. A summary of the results will be presented in the Experimental Results section.

NITROGEN TRANSFER

Water samples were taken for two runs (293 and 375) at inlet and outlet stations to determine the rate of nitrogen transfer relative to that of oxygen. This information was necessary to properly calculate oxygen mass transfer coefficients from the measured oxygen concentrations, since the nitrogen concentrations and mass transfer affect the oxygen transfer. The way in which these processes were modeled is discussed in Section VII, in the "Data Reduction Program" subsection. Quantitative analysis for dissolved gases was performed by a combination of vacuum degassing and mass spectrometry.

Water samples were taken from the inlet line to the U-tube feed tank and from the tee at the U-tube exit. Because the analytical technique could not differentiate between dissolved and entrained gases, considerable care was taken to try to eliminate air bubbles from the sample. The samplers were thoroughly cleaned, evacuated, and then pressurized with helium before sampling. Since no entrained gases were present in the inlet water, the sampling technique was straightforward. The sampler was attached to the feed tank line (after water purging the connecting line). The two valves between the line and sampler were then opened allowing the water to compress the helium to the pump discharge pressure. The upper valve on the sampler was then opened, allowing the helium to escape and water to flow. When approximately one liter had been flushed through the sampler, the sample was taken.

The outlet water sample required revised equipment and procedure because of entrained gases. A long de-entrainment column was placed between the sampler and sample station to remove entrained air from the water to be sampled. Water flowed by gravity into the middle of the de-entrainment column until the column was overflowing; water was then withdrawn for sampling from the bottom of the column. The helium pressurized sampler was reduced to atmospheric pressure and then attached to the sample system after purging of the connecting lines with water from the column. The sampler was then allowed to fill (by gravity flow) until approximately one liter had been flushed. The sample was then taken. While the sampler was filling, the column was still overflowing.

Clear tubing connecting the column to the sampler enabled observation of any entrained gases entering the sampler. The tall narrow column negated any appreciable effects of surface aeration.

Subsequently, in the analytical laboratory, dissolved oxygen and nitrogen were removed from the sample by vacuum degassing. The total quantity of gas was determined from the ideal gas law in a system of known volume. A gas sample was then analyzed on a mass spectrometer to obtain the quantitative nitrogen-oxygen ratio. The results of these analyses for the four samples will be presented in the Experimental Results section.

SILTING STUDIES

Experimental studies of silting/scouring were conducted using a concentric pipe return bend. The objective of the effort was to determine the minimum velocity necessary to begin scouring and transporting particles out of the bottom of the return bend and up the U-tube upleg. Four particle size ranges were used: U.S. Sieve No. 30-35 (0.50-0.60 mm) glass beads, U.S. Sieve No. 14-18 (1.00-1.41 mm) ground glass particles, U.S. Sieve No. 8-10 (2.00-2.38 mm) gravel, and U.S. Sieve No. 3.5-5 (4.00-5.66 mm) glass beads.

The glass U-bend on the 45-foot U-tube was removed and replaced with a concentric return configuration, shown in Fig. 6. Water flow came down the center pipe and went out the side arm. Since the study was concerned with water-solid interaction, no air was introduced through the venturi. A series of runs was made without solids to calibrate the water flow vs head loss characteristics of the system. Then, five scouring runs were made - two with the 3.5-5 mesh beads and one each with the other particle sizes.

A typical test run commenced by loading the return bend (through the venturi aspirator) with solids to some level, usually below the downleg terminus. A small ΔH was set across the U-tube and flow was

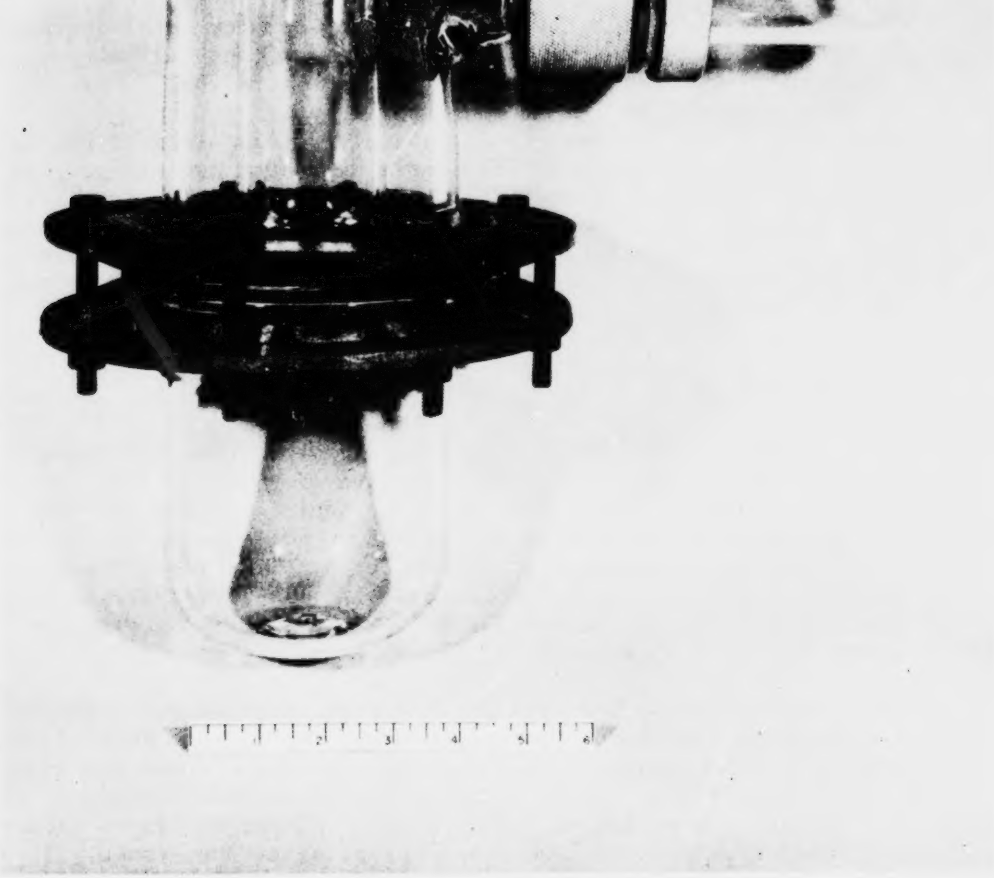


Figure 6. Concentric Return Assembly Used in Silting Experiments (Scale is in inches)

started. The action and depth of scour of the solids was recorded as the system ΔH and water flow rate were increased. Water flow rate measurements were made as a check on the calibration runs. A screen was placed in the surge tank to catch solids that were flushed out of the return. The results of these tests are presented in the next section.

SECTION V

PILOT-SCALE EXPERIMENTAL RESULTS

AERATION STUDIES

Four hundred ten (410) test runs were performed to evaluate the aeration characteristics of the pilot-scale U-tube. Not all of the instrumentation discussed in the previous section was included from the first run, e.g., the third dissolved oxygen probe was not available before Run 139. In general, instrumentation was added as the value of additional measurements became apparent.

A summary of the tests, including an outline of the system parameters and measurements which were made, is shown in Table 1. The experimental data acquired for Runs 1 through 94 (using the center-plug aspirator) were not of much value because of the poor performance of this aspirator. Therefore, they are not included in this report. Appendix A contains all data for runs using the venturi aspirator. It should be noted that Appendix A also contains other information which was generated from the experimental data using the data reduction program which will be described in the Analytical Studies section. Table 1 and Appendix A explain which of the values are experimental data and which are calculated values. The two sets of values are combined in Appendix A for the convenience of the user.

Figures 7 and 8 illustrate typical trends of the test data. In these two figures, the applicable oxygen transfer data have been adjusted to a standard set of conditions (the original data had varying inlet D.O. and some variations in temperature and ambient pressure) so that they can be plotted meaningfully. The abscissa on each graph is the amount of oxygen supplied in mg/l. This quantity is directly related to the initial air-to-water volume ratio:

Oxygen supplied, mg/l = 280 (air/water at 14.7 psia, 68°F)
= 263 (air/water at 13.8 psia, 68°F)

It can be seen that the exit D.O. concentration increases, although with a decreasing rate of increase, as the amount of oxygen supplied is increased. Although not obvious from Fig. 7, the curves will not be asymptotic to the saturation concentration (9.08 mg/l) because of the ability of U-tube systems to raise the D.O. level above the ambient saturation concentration, if designed for such high exit D.O. levels. As the water velocity is decreased, the exit D.O. concentration increases and the overall pressure drop decreases; therefore, the experimental results clearly illustrate the advantages of low water velocities in system performance. There are tradeoffs, however, when the system economics are considered, since lower velocities require larger capital expenditures. Such tradeoffs need to be considered in each individual design case.

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TABLE 1. SUMMARY OF MEASUREMENTS MADE IN U-TUBE AERATION EXPERIMENTS

Run Numbers	Aspirator Type	U-Tube Depth* (ft-in.)	Water Depth Above Aspirator Inlet (in.)	Dissolved Oxygen Measurements			Pressure Measurements		
				Aspirator Exit	U-bend Exit	Platform	Aspirator Exit	U-bend Entrance	Platform
1-25	center-plug	36-9	6 & 12						
26-94	center-plug	45-0	12				x	x	
95-138	venturi	45-5	7				x	x	
139-167	venturi	45-5	7	x			x	x	
168-219	venturi	18-10	7	x			x	x	
220-252	venturi	8-11	7		x		x	x	
253-263	venturi	8-11	7				x	x	
264-318	venturi	27-11	7			x	x	x	
319-325	venturi	27-11	7				x	x	
326-410	venturi	36-6	7		x		x	x	x

*Depth is distance from extrance of U-tube (entrance of aspirators) to bottom of return bend; in some sections of this report, these are rounded to the nearest foot.

The following measurements were made for all runs: water temperature at entrance and exit, water flow rate, air flow rate, ambient pressure, ambient air temperature, D.O. at entrance and exit, and overall head loss across the system.

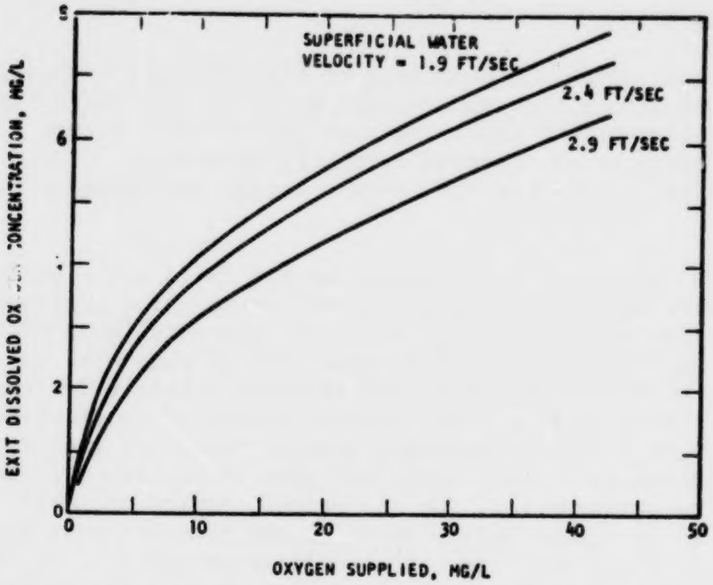

Figure 7. Dissolved Oxygen Increase Across 28-ft Deep Experimental U-Tube (reduced to standard conditions of 68° F, 1 atm, zero inlet D.O.)

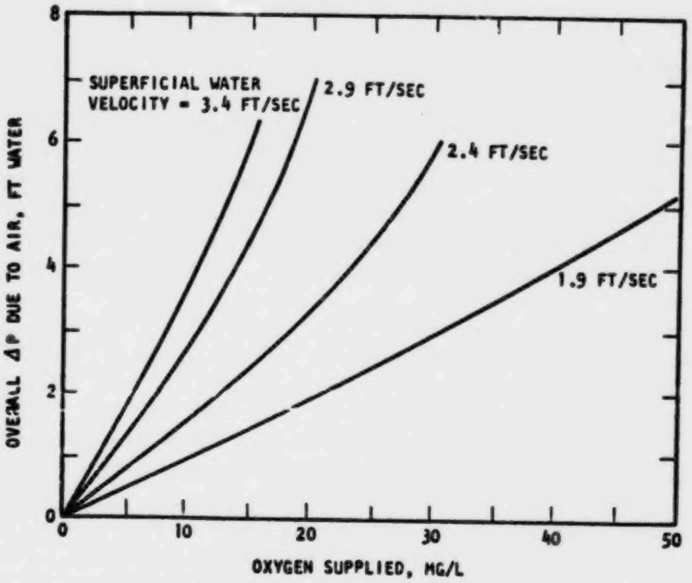

Figure 8. Overall Pressure Drop Due to Air Across 28-ft Deep Experimental U-Tube

ASPIRATOR EVALUATION

It was noted soon after the beginning of experimentation that permanent pressure losses across the center-plug aspirator were quite large. Since these losses were a major fraction of the total energy losses, design began early on an improved (venturi) aspirator. It was apparent soon after installation that the venturi design was markedly superior.

A comparison of pressure drop between the two units was first made using water. A series of runs was made with the center-plug aspirator at fixed contraction ratios and variable water flowrate (Runs 73-94). Similar data were available from several sets of runs with the venturi. A plot of the permanent pressure loss vs water velocity for the two aspirators is shown in Fig. 9 for several values of contraction area ratio, E (defined as cross-sectional area of the 2.067-inch I.D. pipe divided by minimum flow cross-sectional area in aspirator). It is apparent that the pressure loss for the venturi aspirator (which has a fixed E of 8.0) is approximately equal to the pressure loss for the center-plug aspirator with the contraction ratio set at 2.9. It was possible to obtain a given amount of aspiration with the venturi aspirator at a much lower permanent head loss than with the center-plug aspirator. Another advantage of the venturi aspirator concept is that the minimum dimension of the flow passage remains higher than for a center-plug aspirator, thus reducing the chance of plugging.

AIR BUBBLE CHARACTERIZATION

High-speed motion pictures were taken of the two-phase fluid flow during nine runs with each type of aspirator in a U-tube 45-ft deep. These pictures were used in determining various air bubble characteristics. A random sample of approximately 25 bubbles in each of several frames was used for determining bubble shapes, sizes, and slip velocities for each run. Measurements were made from projected enlargments of the motion pictures.

Figures 10, 11, and 12 show enlargements of six frames, selected at random, from the motion pictures for Runs 131, 136, and 137. In each figure, the top photograph shows a section in the U-tube located approximately 7 ft below the aspirator outlet (the flow direction is from top to bottom), and the bottom photograph shows the glass return bend (with flow from right to left). It can be seen that the air bubbles are approximately oblate spheroids, with larger bubbles generally having greater eccentricity than small bubbles. There is some observable flattening of the bubble leading surfaces as compared with the trailing surfaces; however, this is not a large effect except for the largest bubbles.

Table 2 summarizes the results for runs with the venturi aspirator. The pictures taken during runs with the center-plug aspirator, as well

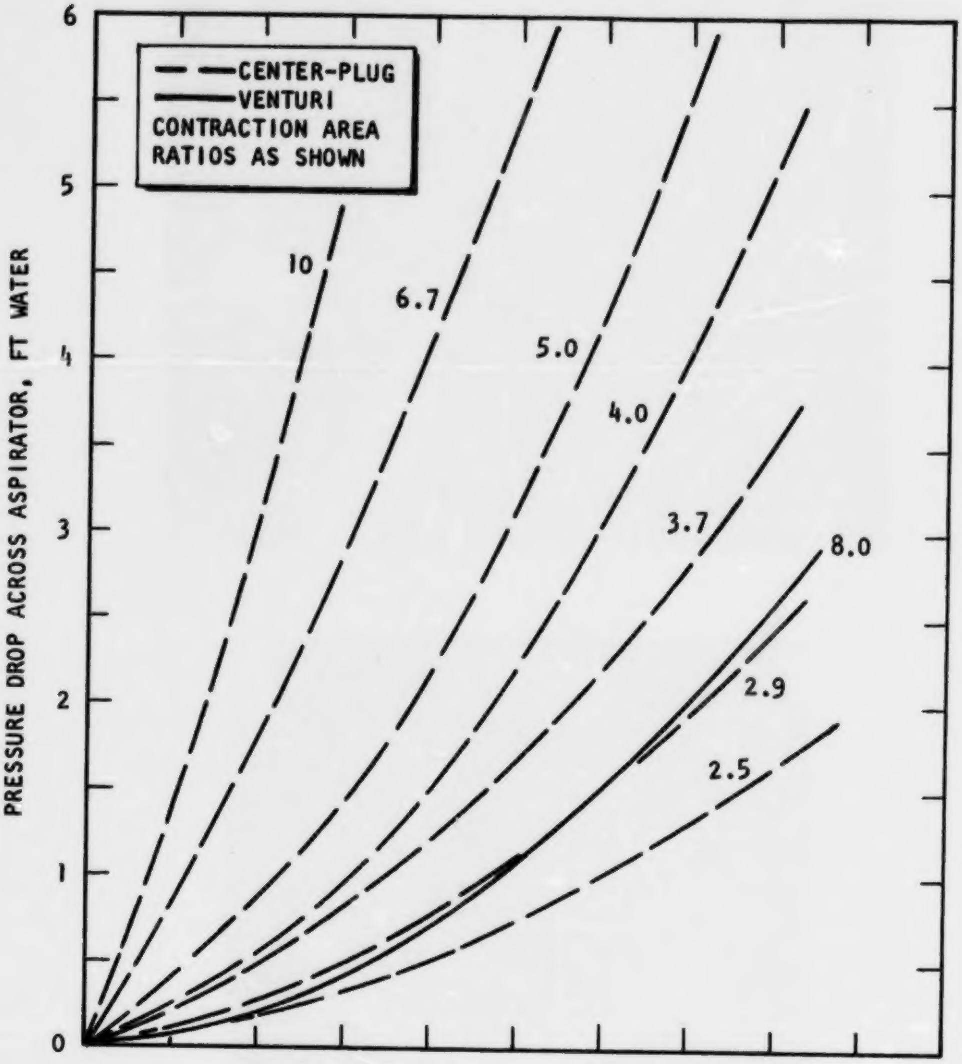

Figure 9. Comparison of Pressure Drop Across Center-Plug and Venturi Aspirators

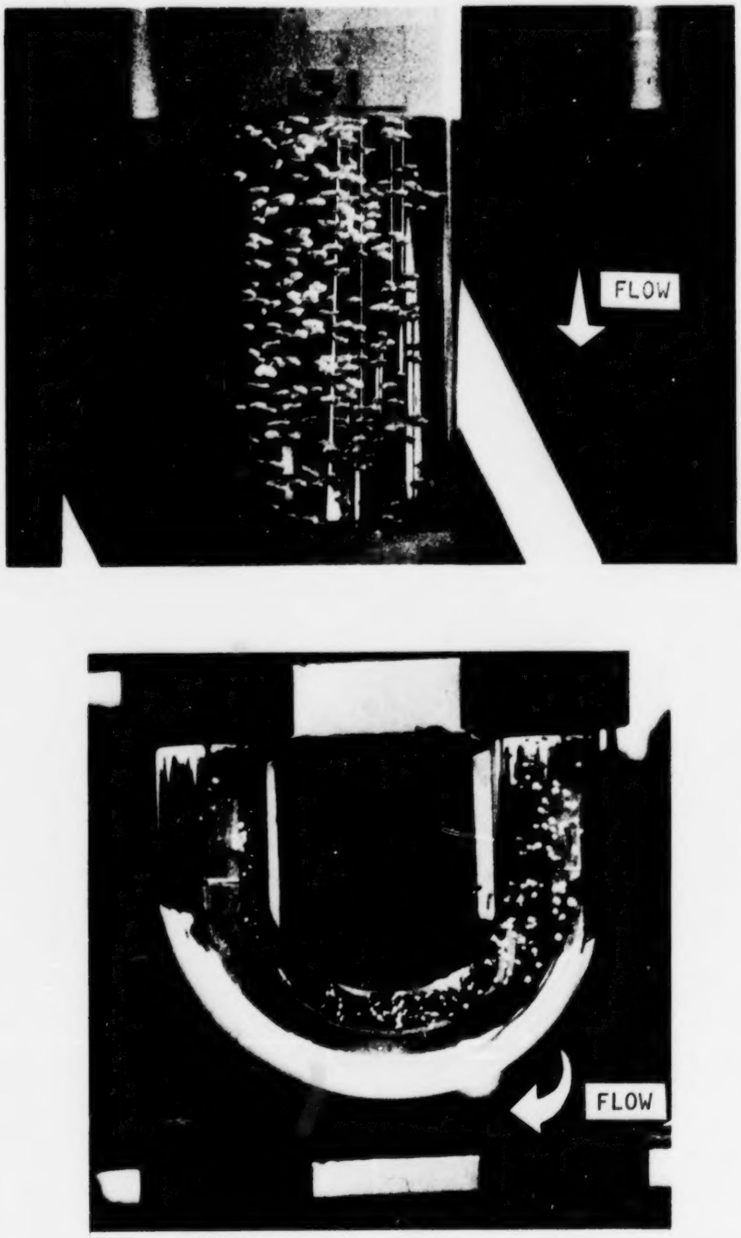

Figure 10. Photographs of Two-Phase Flow in U-Tube (Run 131, superficial water velocity = 2.9 ft/sec, initial air/water volume ratio = 0.014 at 1 atm, 68° F)

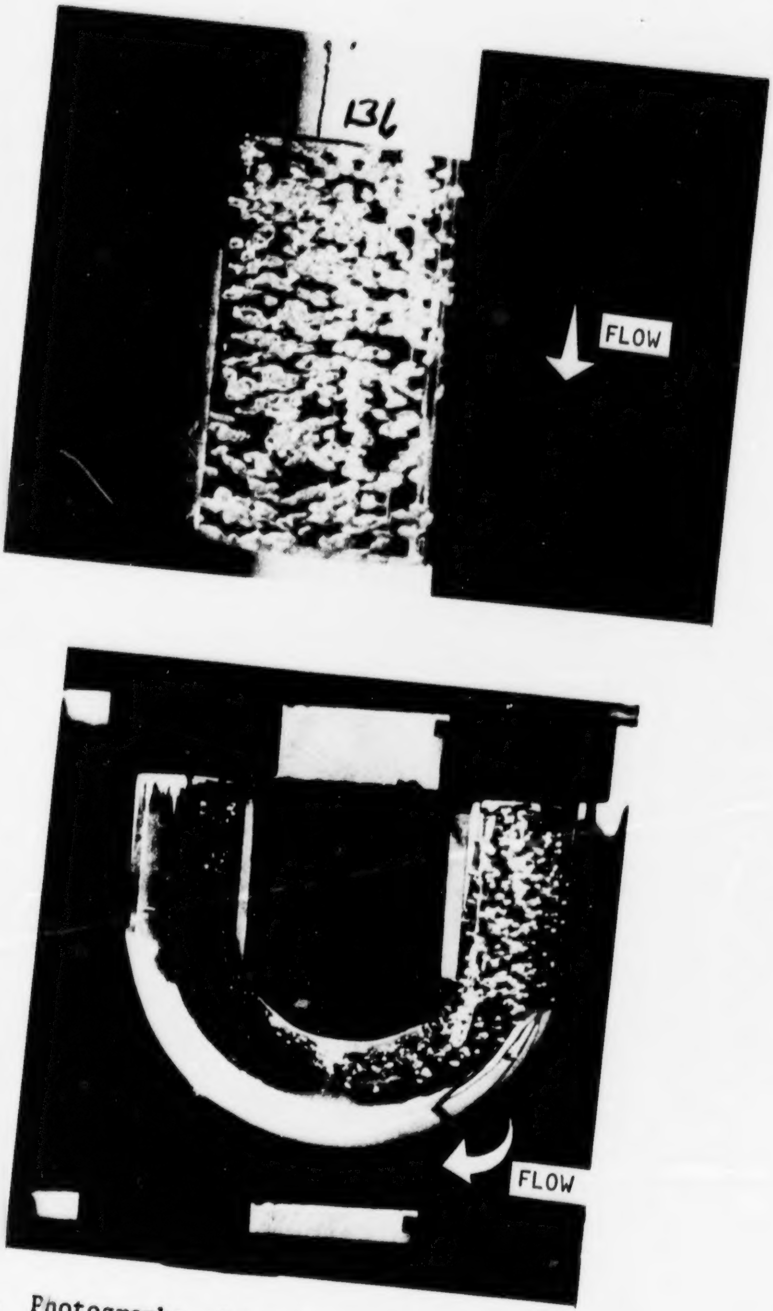

Figure 11. Photographs of Two-Phase Flow in U-Tube (Run 136, superficial water velocity = 2.4 ft/sec, initial air/water volume ratio = 0.063 at 1 atm, 68° F)

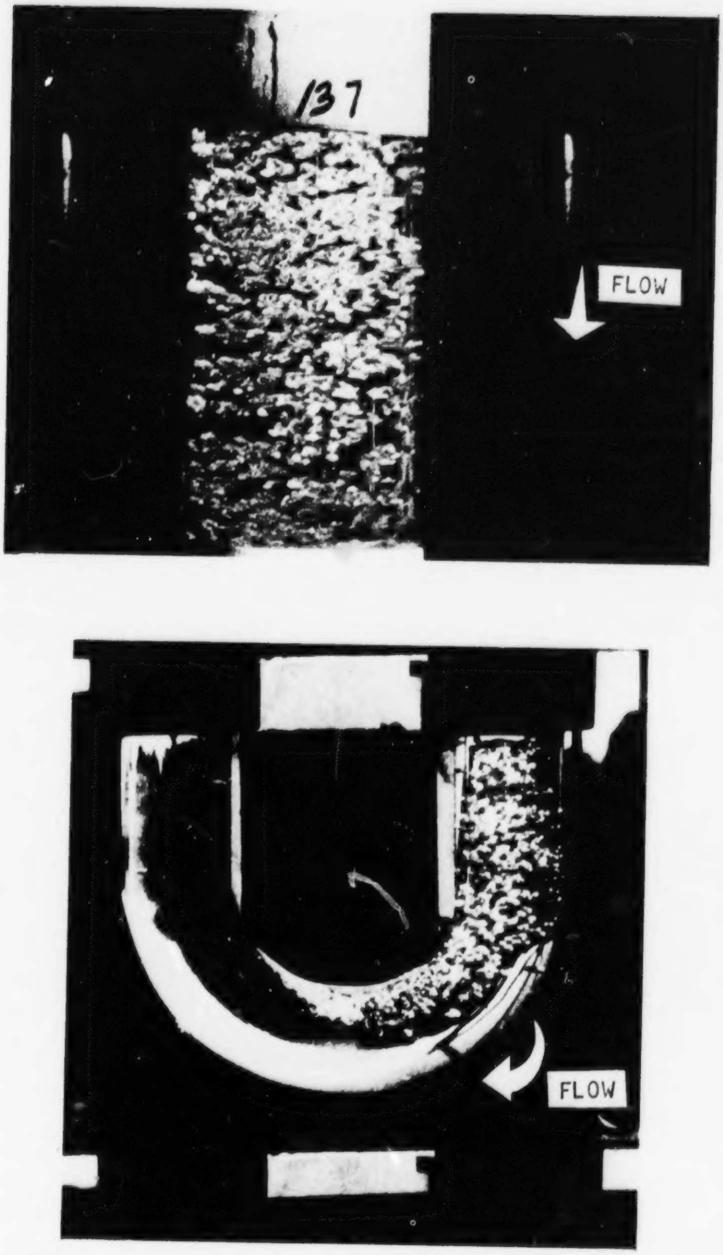

Figure 12. Photographs of Two-Phase Flow in U-Tube (Run 137, superficial water velocity = 2.0 ft/sec, initial air/water volume ratio = 0.088 at 1 atm, 68° F)

TABLE 2. SUMMARY OF TWO-PHASE FLOW CHARACTERISTICS IN U-TUBE WITH VENTURI ASPIRATOR

Run Number	Superficial Water Velocity (ft/sec)	Initial Air/Water Volume Ratio at 1 atm, 68°F	Location in U-tube	Bubble Mean Major Diameter (inch)	Bubble Mean Minor/ Mean Major Diameter	X, Total Area/ Bubble Volume ($inch^{-1}$)	Mean Slip Velocity (ft/sec)
131	2.9	0.014	top	0.18	0.53	39.8	0.08
			bottom	0.18	0.55	39.2	
132	2.4	0.046	top	0.17	0.61	40.2	0.19
			bottom	0.17	0.52	41.3	
133	2.0	0.066	top	0.19	0.53	40.2	0.24
			bottom	0.20	0.53	36.0	
134	1.9	0.022	top	0.21	0.47	29.7	0.20
			bottom	0.20	0.47	42.9	
135	2.8	0.039	top	0.20	0.46	40.4	0.23
			bottom	0.19	0.45	45.6	
136	2.4	0.067	top	0.23	0.46	26.3	0.01
			bottom	0.20	0.49	37.6	
137	2.0	0.094	top	0.19	0.59	37.8	0.23
			bottom	0.19	0.48	42.3	
138	2.8	0.045	top	0.19	0.54	39.8	0.20
			bottom	0.19	0.47	41.7	
Mean values for eight runs			top	0.19	0.52	36.9	0.17
			bottom	0.19	0.50	40.8	

as Run 130 with the venturi aspirator, were of poorer quality than the later eight runs represented in Table 2; therefore, the information from these eight runs was used as the primary basis for characterizing the two-phase flow. The superficial water velocity is, as previously defined, the velocity with which the water would flow at the measured flow rate if the air were not present. In all cases, this velocity was calculated from the measured water flow rate and the known pipe diameter. The initial air-to-water volume ratio expresses the amount of air introduced in the aspirator before any gas is dissolved. The "top" location in the U-tube was a section located approximately 7 ft below the aspirator outlet in the ten-foot length of glass pipe. The "bottom" location was about six inches above the bottom of the glass return bend section. The mean diameter values given in Table 2 are arithmetic mean values of the approximately 50 to 75 randomly chosen bubbles for each case (i.e., approximately 25 bubbles chosen from each of 2 or 3 frames). The ratio of mean minor diameter to mean major diameter is given because it has greater statistical validity than the mean of the individual ratios for each bubble. The total air-water interfacial area per unit volume of air, X, is the variable actually used in later analytical studies to characterize the effects of bubble size and shape on the mass transfer. It was calculated by summing the values of interfacial area divided by bubble volume for each individual bubble in a run (treating the bubbles as oblate spheriods with the measured major and minor diameters) and dividing by the total number of bubbles measured for that run. This variable thus combines the effects of bubble size and shape distribution, and is not a function of the absolute bubble population or air-to-water ratio. It can be seen from the results in Table 2 that there is no apparent effect of water velocity or air-to-water ratio on the bubble shapes or sizes. Even more surprising, however, is the absence of a difference in bubble size between the top and the bottom of the U-tube, a distance of 36 ft. If most of the bubbles remained as discrete entities throughout their passage through the down-leg, there would be a detectable change in mean bubble size between the top and bottom. Apparently, there is enough net bubble coalescence to compensate for the increase in pressure (plus some small amount of gas dissolution). The balance of these two effects may not be neutral in other physical situations; however, the pilot-scale U-tube with venturi aspirator and 45-ft length seems to be characterized by approximately constant air bubble size throughout at least the down-leg.

Slip velocity is defined as the difference between the actual (not superficial) water velocity (u_w) and the bubble velocity (u_a), i.e., $u_s = u_w - u_a$. It is an important parameter in the evaluation of mass transfer coefficients through the U-tube. With this definition the slip velocity is positive in the down-leg and negative in the up-leg. The slip velocity values are inherently less accurate than the other experimental data because the possible error in determining both water velocity and bubble velocity is large with respect to their difference (slip velocity). It was not possible to obtain meaningful slip velocities at the return bend because of the flow curvature there.

Figure 13 shows the experimental slip velocities at the top of the downleg for the venturi and center-plug aspirators. The data for the center-plug aspirator show more scatter than the venturi aspirator data, which is reasonable since the latter were taken from pictures with greater magnification, hence, improved definition. In spite of the scatter, the data suggest a mean slip velocity of about 0.2 ft/sec, especially in the case of the venturi aspirator. The slip velocity appears to be independent of water velocity or air-to-water ratio over the ranges of variables included in these two-phase flow tests.

NITROGEN TRANSFER

Procedures and apparatus for the analysis of dissolved gases have been discussed in the Experimental Studies section. The results for the four samples (i.e., entrance and exit samples for Runs 293 and 375) are shown in Table 3.

TABLE 3. RESULTS OF CHEMICAL ANALYSIS FOR DISSOLVED NITROGEN

Run Number	293	375
Superficial water velocity (ft/sec)	1.9	1.4
Air/water at 1 atm, 68°F	5.8	7.0
D.O. concentration (mg/1):		
entrance	2.2	1.1
exit	7.4	5.6
D.N. concentration (mg/1):		
entrance	3.8	2.6
exit	16.8	12.9
D.N. change/D.O. change	2.5	2.3

It can be seen that the D.O. concentrations in Table 3 disagree somewhat with the meter readings for entrance and exit D.O., stations 1 and 12 (Appendix A). This discrepancy is thought to be due primarily to errors in the sampling and analytical procedures. However, this is not of particular importance since the significant results are the ratios of D.N. change to D.O. change. These ratios were used in estimating nitrogen mass transfer coefficients from the experimental oxygen mass transfer coefficients, using the data reduction programs as discussed in Section VII.

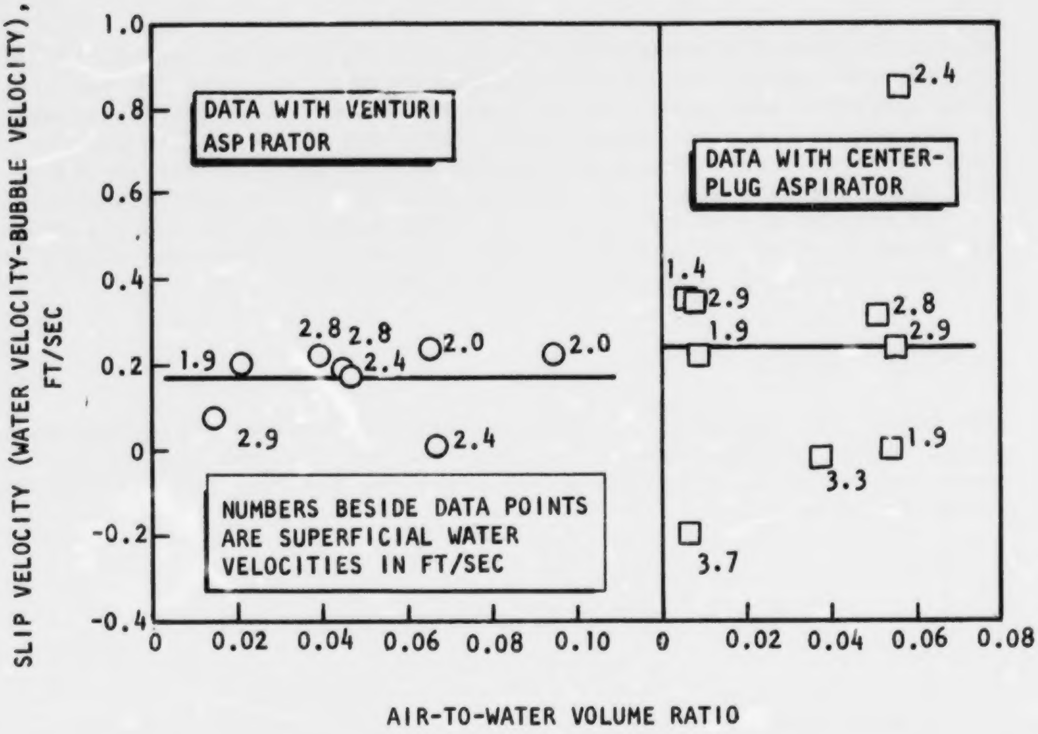

Figure 13. Air Bubble Slip Velocities Near Top of U-Tube

SILTING STUDIES

The objective of the silting-scouring studies was to develop a basis for designing U-tubes so that they would be free from plugging problems due to silting.

The first part of this section briefly describes some relevant physical factors and previous experimental studies in the area of silting and scouring in pipe flow. The remainder of the section contains the experimental data and information on scouring generated during this investigation.

The behavior of a moving slurry containing solid particles of greater density than the liquid can be described at various velocities as follows:

1. At very low velocities, the particles will settle out under free or hindered settling.
2. Above a certain "minimum velocity" there will be no particles settling out of the slurry; however, a vertical concentration gradient will exist.
3. When the velocity exceeds the "standard velocity", there will be adequate mixing to eliminate any appreciable vertical concentration gradient.

In a sewage stream, the organic materials and most of the other potentially cohesive materials will be less dense or, at most, of comparable density to water. Therefore, these will be less likely to cause settling problems than the more dense materials such as sand, rocks, bottles, tin cans, etc.--materials which are essentially noncohesive. With noncohesive materials, the movement of solid particles depends only upon the physical properties of the individual particles such as size, shape, and density, and upon their relative position with respect to other particles. Natural sediments are irregular in shape, and, therefore, the definition of size as a single length or diameter must be made arbitrarily. One of the common definitions is the sieve diameter, the size of sieve opening through which the given particle will just pass. In any particular sediment, the sizes of the individual particles may vary over a wide range. However, since larger particles will (with other factors being constant) settle out of a slurry more readily than smaller particles, the design approach taken in the subsequent discussions is to prevent sedimentation of particles of a specific maximum sieve size. Then, any smaller particles will not settle out, but it will be necessary to prevent particles larger than the design size from entering the U-tube.

A single solid particle in a stationary fluid will be acted upon by forces due to buoyancy, gravity, and fluid friction (usually lumped into the "drag" force). A particle released from rest will accelerate until these forces just balance; the resulting velocity is the "terminal velocity". If the upward fluid velocity in a vertical pipe containing a solid particle is equal to the terminal velocity of the particle, then the particle will have no net vertical movement. If the upward fluid velocity exceeds the terminal velocity, the particle will be transported upward. Curve No. 1 in Fig. 14 shows the terminal velocity of quartz or sand spheres (specific gravity = 2.64) as a function of particle size. Irregular particles will have lower terminal velocities than spheres, of the order of 60 percent of the spherical particle terminal velocity (Ref. 10), represented by curve 2 in Fig. 14.

Ensuring that no restrictive sediment bed will develop on the bottom of the U-tube may require higher velocities than those needed to exceed the settling velocities of the particles. This flow situation is much less tractable, analytically. Several generalizations which have been reported in the literature, all based at least partly on experimental data, are described in the following paragraphs, and results are included in Fig. 14.

Spells (Ref. 11) developed a correlation based upon consideration of the Froude number (to represent gravitational forces) and the Reynolds number (to account for viscous forces) plus experimental data (for particles approximately 50 to 200 microns):

$$\frac{u^2}{g_c \, D_p} = B_1 \left(\frac{D \, u \, \rho_m}{\mu}\right)^{0.775} \left(\frac{\rho_p - \rho}{\rho}\right)$$

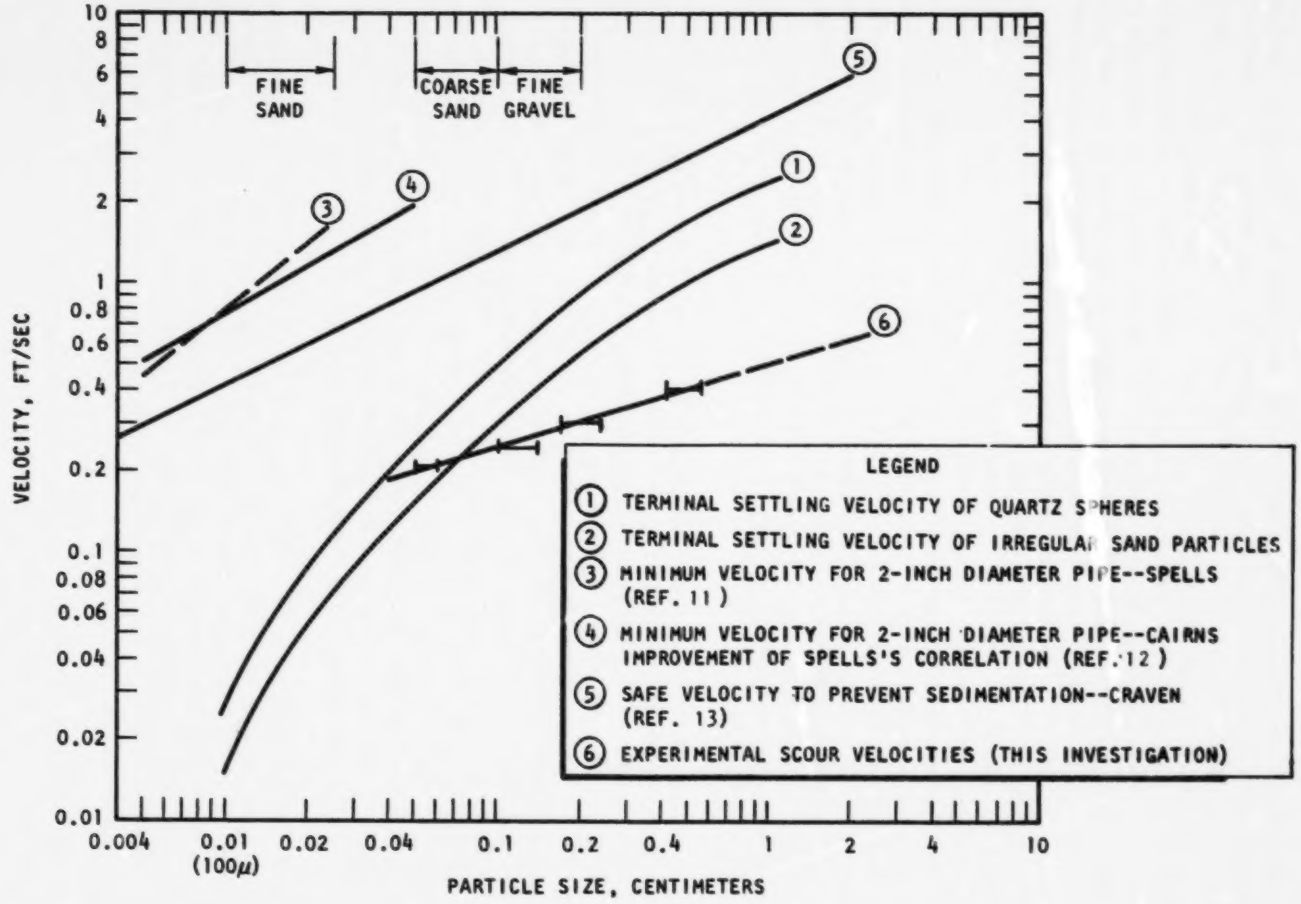

Figure 14. Effect of Particle Size on Scour Velocity

where D_p = particle diameter, D = pipe diameter, ρ_p = particle density ρ_m = mean density of the slurry, and B_1 is an empirical constant which is reported as 0.0251 for the "minimum velocity" and 0.0741 for the "standard velocity". This correlation has given only rough agreement with other published data. Cairns (Ref. 12) considered Spells' equation and used additional data to give his recommended improved form of the equation:

$$\frac{u^2}{g_c\, D_p} = 9.8\ C^{0.3}\left(\frac{D\, u\rho}{\mu}\right)^{0.3}\left(\frac{\rho_p - \rho}{\rho}\right)$$

where C is the solids concentration in volume percent, and the particle size, D_p, is in feet. The results of parametric calculations with each of the above equations are presented in Fig. 14 (curves 3 and 4, respectively).

Curve number 5, shown in Fig. 14, is given by Craven (Ref. 13) and is the one for which the experimental data used to generate it most closely approximate the conditions expected in a typical U-tube application to a sewer line. Therefore, it might be expected to be the most reliable design tool of all the correlations shown in the figure. Craven found that no permanent deposit of sediment would occur in full-flowing pipes if:

$$\frac{Q}{D^2\ D_p^{1/2}\ g^{1/2}\left(\frac{\rho_p - \rho}{\rho}\right)^{1/2}} > 2.5$$

where Q is the volumetric flowrate through the pipe. The expression on the left side of the equation is dimensionless.

Relatively few applicable studies were found in the limited literature search which was conducted. No work was found which investigated silting or scouring in vertical or curved pipes, which are the cases of interest in a U-tube. Therefore, brief experimental studies were conducted as a part of this project. The experimental procedures for the silting studies were discussed in the Experimental Studies section. One difficulty in evaluating and applying the scouring data was the uncertainty in defining and evaluating values for scour velocity (i.e., that minimum velocity necessary to cause settled particles to dislodge from the solid bed and be transported into the up-leg of the U-tube). Figure 15 illustrates the concentric return bend assembly used in the experiments (a photograph of the assembly was previously given in Fig. 6). It was realized that a non-uniform velocity profile existed in a direction perpendicular to the solid bed surface. Since it was not possible to determine the actual surface velocity (which would be a most reasonable definition for scour velocity), the scour velocity was defined as the average water velocity through the area formed by an imaginary cylinder extending from the down-leg bottom to the solids bed

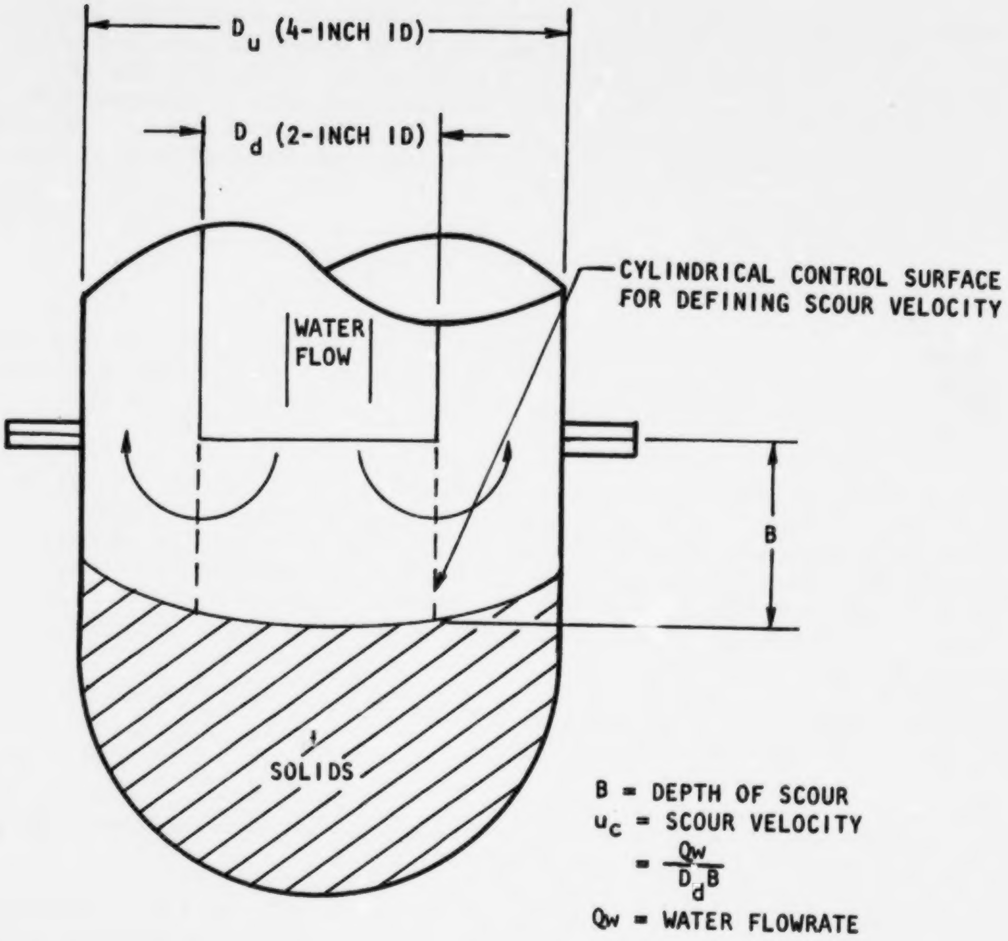
D_u (4-INCH ID)
D_d (2-INCH ID)
CYLINDRICAL CONTROL SURFACE FOR DEFINING SCOUR VELOCITY
WATER FLOW
B
SOLIDS
B = DEPTH OF SCOUR
u_c = SCOUR VELOCITY
$= \frac{Q_W}{D_d B}$
Q_W = WATER FLOWRATE

Figure 15. Diagram Illustrating Analysis of Experimental Scour Data

surface (see Fig. 15). The scour velocities were evaluated at constant water flowrate by determining the distance B at which solids ceased to be removed from the solid bed at the bottom of the return bend. With the depth of scour and U-tube ΔH as data, average scour velocities were determined for each particle size.

A series of scour depth and U-tube head loss measurements were taken for each test run. Head loss measurements enabled evaluation of water velocity from a series of calibration runs. The scour velocity was determined at each depth of scour, and an average was taken for the run.

Velocities showing large deviations from the average (usually at the start of a run) were discarded. The results are as follows:

Particle Size Range (mm)	Number of Determinations	Range of Scour Velocity (ft/sec)	Average Scour Velocity (ft/sec)
4.00 - 5.66	6	0.39 - 0.42	0.40
2.00 - 2.38	10	0.29 - 0.32	0.31
1.00 - 1.41	5	0.23 - 0.25	0.24
0.50 - 0.60	5	0.20 - 0.21	0.20

These data are represented by curve 6 in Fig. 14. This particular curve in Fig. 14, it should be remembered, is a representation of scour velocities of a particular concentric return bend at the bottom of a U-tube for particles in the range 0.50 to 5.66 millimeters. Caution should be used in extrapolating the results beyond this particle size range or to different systems. However, the results do give some basis for determining velocities necessary to keep a U-tube return bend free of solids with diameters less than 1/4-in.

It can be seen that there are considerable differences between the data obtained herein and predictions from various other investigations for velocities required to scour or prevent silting (Fig. 14, curves 1 through 5). The fact that the required velocities from this investigation are lower than the others plotted in Fig. 14 is due at least partly to the definition of scour velocity used in this case. The actual velocity at the bed surface was undoubtedly higher than the average velocity (based on a constant velocity profile across the flow cross-section at the minimum point) which was used to calculate the values given in the above table and in Fig. 14.

Of the relationships illustrated in Fig. 14, it is judged that design velocities selected from approximately the range recommended by curve 5 should be used to prevent sedimentation in the bottom of a U-tube. Thus, it should be possible to prevent sedimentation of sand and rock particles up to the size of fine gravel by designing a U-tube for minimum water velocities of approximately 1.5 to 3 ft/sec. The experimental results of this investigation suggest that these may be rather conservative. This is a very practical requirement for a U-tube application; therefore, preventing sedimentation in a U-tube system is not expected to be a serious design problem.

SECTION VI

FULL-SCALE EVALUATION TESTS

Several full-scale U-tube systems were installed in sanitary sewer lines in Jefferson Parish, Louisiana, and Port Arthur, Texas, under EPA Grants 11010 ELP and 11010 DYO, respectively. These grant projects have been reported in Ref. 14 and 15. Design and optimization studies were conducted during this project in support of these EPA grant projects. Subsequently, field evaluation tests were made at each location. The following sections describe the application sites, design approach, final U-tube system designs, and evaluation tests that were conducted.

JEFFERSON PARISH

Application Sites

Jefferson Parish is adjacent to the west side of Orleans Parish in which the city of New Orleans lies. The portion of Jefferson Parish in which the aeration systems were installed is bounded by Lake Pontchartrain on the north and the Mississippi River on the south. More specifically, the sewer lines under study collect waste water from part of the area north of Air Line Highway and flow northward to the Helois Treatment Plant. This area is quite level and much of it is below the elevation of Lake Pontchartrain and the Mississippi River at this point. The difficulties of sewer construction caused by the high ground water level and low rigidity of the soil have necessitated the use of minimum slopes on gravity sewer lines plus numerous pumping stations. The net waste water velocities are small compared with those in many areas, and there have been septicity problems in the sewers. It is, of course, important to prevent septic (anaerobic) conditions from developing in a sewer line because of the resultant odor, corrosion, and subsequent treatment plant problems which this can cause. The Jefferson Parish Department of Sanitation has been active in improving its sewer systems to eliminate many of the potential trouble spots, primarily by installing additional lift stations and more force mains to decrease the average sewage residence times. This project had the objective of investigating aeration as a method for septicity control.

The "Old Metairie" section of Jefferson Parish, Louisiana, was selected for U-tube aeration installations because of its need for additional sulfide control in force mains. Two sites (designated locations 5 and 7) in the Old Metairie area which exhibited unusually high corrosive attack and gas odor were selected for installation of venturi aspirated U-tube aeration devices.

Design Approach

The primary objective of each aeration facility was to efficiently dissolve as much oxygen in the waste water stream as possible within the particular constraints of each chosen site.

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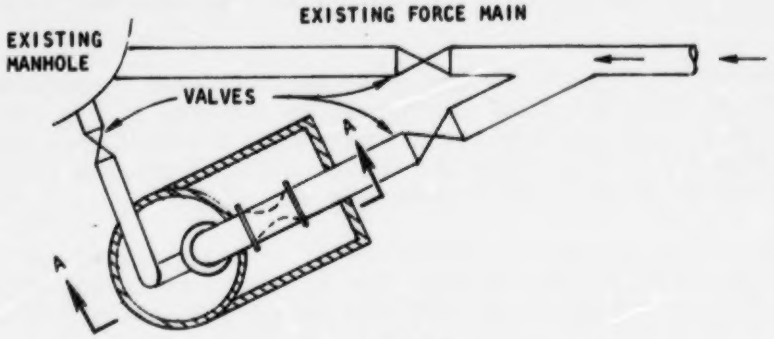
A very important consideration which imposed constraints on the designs was that they should not offer any opportunity for plugging. Most of the specifications for lift pumps in this area require passage of a "3-inch-diameter sphere" (in a few cases, 4-inch diameter is specified). Consequently, in the U-tube designs no cross section with a dimension less than 4 inches was permitted. This imposed a constraint on the minimum flowrate for which an aspirated-air U-tube could be applied. With pressure drops typical of those for the Jefferson Parish designs, the flowrate must be greater than about 300 gpm to keep the required aspirator throat diameter at least 4 inches.

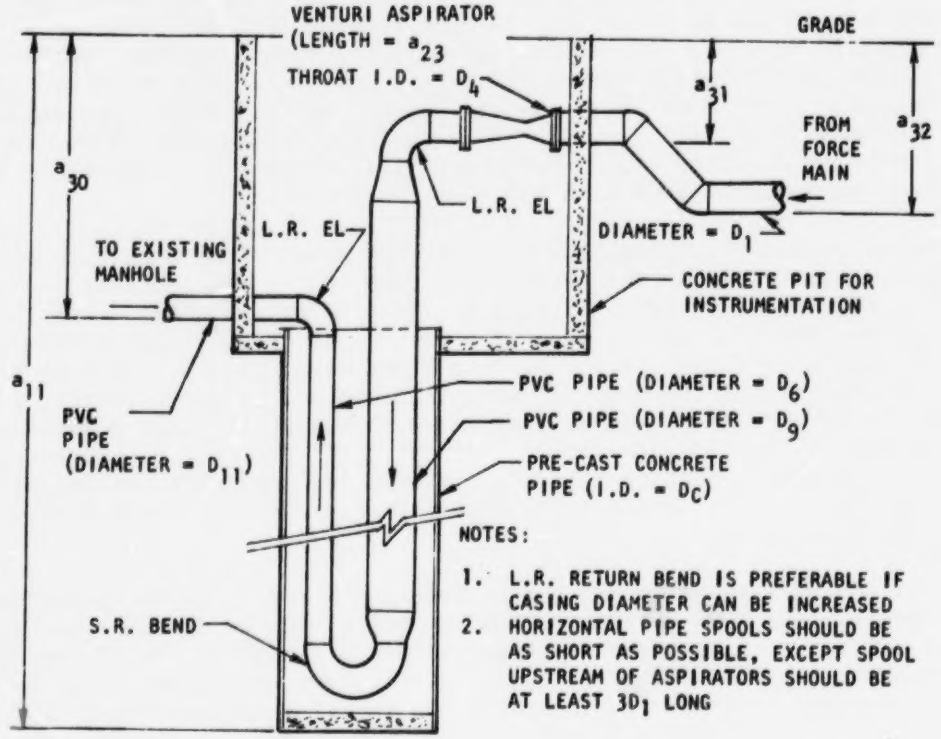
Another possible source of plugging could be the return bend at the bottom of the U-tube. A concentric configuration would have several construction advantages; however, it could produce two possibilities of plugging in this application: the annular space between the inner and outer pipes would be less than 4 inches for these applications, and the abrupt edge at the bottom of the inner pipe could possibly result in some hang-up of material. Consequently, all designs used a literal U-bend between separate down and up pipes, as shown in Fig. 16. It was necessary to ensure that all solid material would be carried up the up-leg and transported from the U-tube system. Although an up-leg velocity of approximately 2 ft/sec would be sufficient to transport sand and prevent silting (as discussed in a previous section), this might not be high enough to transport larger items which could still be passed by the pumps. The Parish design rules for lift pump vertical risers require the velocity to be at least 4 ft/sec. This lower limit on up-leg velocity was also used in these designs.

One major constraint was shared by all of the aspirated-air systems; the throat pressure must be less than the ambient pressure to aspirate air into the flowing water stream. This is not particularly difficult in a gravity-flow system where the pressure at the entrance to the aspirator is merely due to the height of liquid above it. In a force-main application, however, the design is more difficult because the aspirated entrance pressure can be considerably greater than the ambient pressure. If the pressure drop downstream of the aspirator is substantial, the aspirator contraction ratio must be much larger (throat smaller) than for a corresponding gravity flow application. This, in turn, leads to a higher ratio of permanent pressure drop-to-throat pressure decrease, R, since R increases with increasing venturi contraction area ratio. The "permanent pressure drop" across the venturi (the difference between the measured pressures upstream and downstream of the venturi) is generally much less than the equivalent on-phase throat pressure decrease (the difference between the measured upstream pressure and the static pressure at the venturi throat if no air were introduced there). Consequently, R is generally less than 1. High values of R correspond to high-energy losses in the aspirator.

Another set of design considerations centered around the existing system and pump characteristics. Many of the existing lift pumps were operating below their design lifts, and most could also be uprated with larger


EXISTING FORCE MAIN
EXISTING MANHOLE
VALVES
A
A

SITE PLAN


VENTURI ASPIRATOR
(LENGTH = a23
THROAT I.D. = D4
GRADE
a31
a32
FROM FORCE MAIN
a30
L.R. EL
L.R. EL
DIAMETER = D1
TO EXISTING MANHOLE
CONCRETE PIT FOR INSTRUMENTATION
a11
PVC PIPE (DIAMETER = D6)
PVC PIPE (DIAMETER = D9)
PVC PIPE (DIAMETER = D11)
PRE-CAST CONCRETE PIPE (I.D. = DC)
NOTES:
1. L.R. RETURN BEND IS PREFERABLE IF CASING DIAMETER CAN BE INCREASED
2. HORIZONTAL PIPE SPOOLS SHOULD BE AS SHORT AS POSSIBLE, EXCEPT SPOOL UPSTREAM OF ASPIRATORS SHOULD BE AT LEAST 3D1 LONG
S.R. BEND

SECTION A-A (SHOWN SCHEMATICALLY)

Figure 16. Basic Configuration for Aspirated-Air U-Tube Designs in Jefferson Parish Sewer System

impellers without changing motors. There was, however, considerable variation in the characteristics at the sites, and this was considered in the designs.

A number of configurations for these aerators were considered in the process of choosing the final configuration sketched in Fig. 16. A large number of parametric computations were made for different configurations and design conditions using the design computer program previously developed from the pilot-scale U-tube data described.

Typical U-tube parametric design trends are illustrated and discussed in Section VIII, U-Tube Design. The primary conclusions developed during the Jefferson Parish design work are summarized in the following paragraphs.

It was soon found that it is very important to keep the elevation of the aspirator as high as possible and the elevation of the exit line to the manhole as low as possible. Both of these conditions help minimize the required aspirator contraction area ratio, with attendant improvement in system pressure drop characteristics. Having the aspirator as high as possible also is of value in reducing or, in some cases, preventing the upstream force main from partially draining during pump off-cycles. Excessive drainage would have undesirable effects on start-up of the aspirator system each time the pump was operating.

Other parametric calculations led to the conclusions that the velocities in all parts of the aspirated-air U-tube system should be as low as possible within the design constraints. This meant, in this particular application, that the up-leg velocities should be greater than 4 ft/sec but as near to 4 ft/sec as actual pipe sizes would permit. This conclusion also meant that the down-leg velocities should be approximately 1.5 to 2.0 ft/sec to keep them as small as possible while still maintaining proper air bubble entrainment. It was concluded that the added expense of pipe reducers to permit a larger down-leg pipe size was definitely justified by the increase in oxygen transfer which results from the longer residence time.

For the particular conditions of location 5 and 7, it was predicted that some air could be aspirated even without a reduced diameter throat section (i.e., in the elevated pipe without a venturi). As the desired amount of oxygen to be supplied (or exit D.O. concentration is increased, it becomes necessary to constrict the throat cross section to a greater extent. This results in an increase in exit D.O. concentration, but also produces an excessive overall head loss. The rapid increase in head loss for small throat cross-sectional areas is a result of the "magnification effect" previously discussed, which is characteristic of, and an inevitable consequence of, a force main application. The cost in head loss for incremental increases in exit D.O. concentration becomes relatively greater as the exit D.O. levels approach saturation. It was found that the decrease in exit D.O. concentration with increasing water flowrate (producing a reduced residence time for air bubbles in the U-tube) is somewhat less rapid than the increase in head loss. However, this trend again illustrated the importance of keeping the water velocities as low as possible within the design constraints.

An alpha value of 0.8 (ratio of oxygen mass transfer coefficient in waste water of interest to coefficient for "tap water") was used in all the calculations for Jefferson Parish aeration systems. This is the value customarily used by the EPA National Environmental Research Center at Cincinnati, and very similar to the value of 0.82 given in Ref. 16 for fresh raw domestic sewage. If the sewage had no remaining dissolved oxygen and a high initial oxygen demand, the measured oxygen transfer would be less than predicted with the 0.8 alpha factor. The actual amount of oxygen uptake, in such a case, may be even greater than the change in D.O. predicted with an alpha of 0.8; however, the final D.O. level would be smaller than the predicted value because of the high initial oxygen demand. The lower alpha values reported in the literature for various samples of raw sewage may include this effect.

After generating parametric design data, as summarized in the previous paragraphs, the pump characteristics (for the pump upstream of each station) were matched with the flow characteristics of the force main plus the U-tube system to be added. Figure 17 illustrates this procedure. Point A, representing the original operating point before any changes to the sewer system, is located at the intersection of the pump characteristic curve and the original total system head curve. Point B is the new operating point after installation of a U-tube system (there could be many U-tube characteristic curves drawn and, consequently, many different point B's, but an efficient U-tube design was chosen in each case). If the new flowrate, Q_B, was lower than desired, then pump modifications were considered. In most cases, the existing pump and motor could accept a larger impeller without other changes. The pump characteristic curve with a larger impeller is represented by the "up-rated pump characteristic curve" in Fig. 17, and point C is the resulting operating point after installation of a U-tube system.

Designs

The final design characteristics for the two aspirated-air U-tube systems at locations 5 and 7 were established, and specified all the important design parameters which influence the system operation. Careful consideration was also given to aspirator design and instrumentation for the purposes of obtaining good information about the operating characteristics. Such instrumentation would not be required in a strictly operational aeration system, but was most important for these initial development systems. These design characteristics and details of instrumentation and aspirators were used by deLaureal Engineers, Inc. (the consulting engineering firm assisting Jefferson Parish with the grant project) to prepare detailed construction drawings.

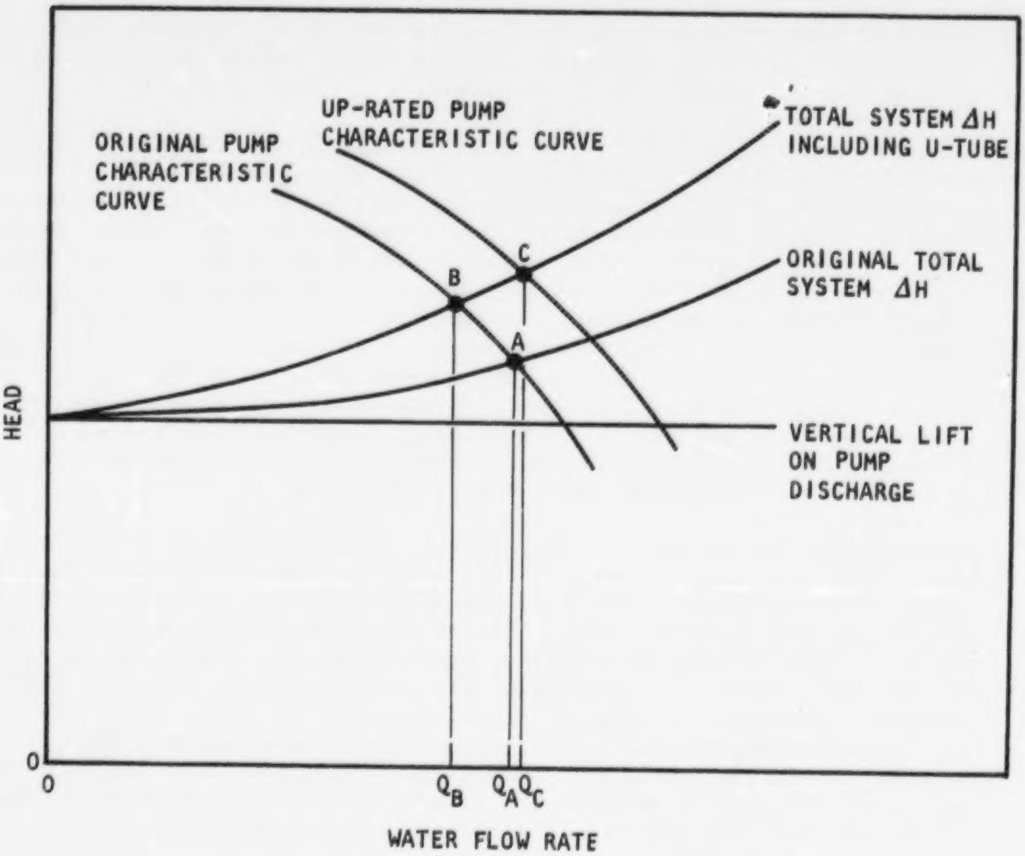


Figure 17. Diagram Illustrating Matching of System and Pump Characteristics

Location 5 is situated at the end of 3000 feet of 12-inch force main through which the nominal flowrate is 1500 gpm while location 7 is at the end of 2050 feet of 10-inch force main through which nominal flowrates of 600 gpm are encountered. The final designs are presented in Fig. 18 and 19, respectively.

The U-tubes were fabricated from fiberglass-reinforced PVC pipe and secured in 4-foot-diameter steel casings with concrete. Details of the U-tube construction and installation can be found in Ref. 14. Venturis selected for this application were essentially standard Dall flow tubes (a type of short-length, contoured venturi flowmeter manufactured by BIF Industries) modified by drilling additional holes in the throat walls for use in air aspiration. Down-leg and up-leg line diameters were selected to provide average superficial water velocities of approximately 1.5 and 4 ft/sec, respectively, at each location. All pipe

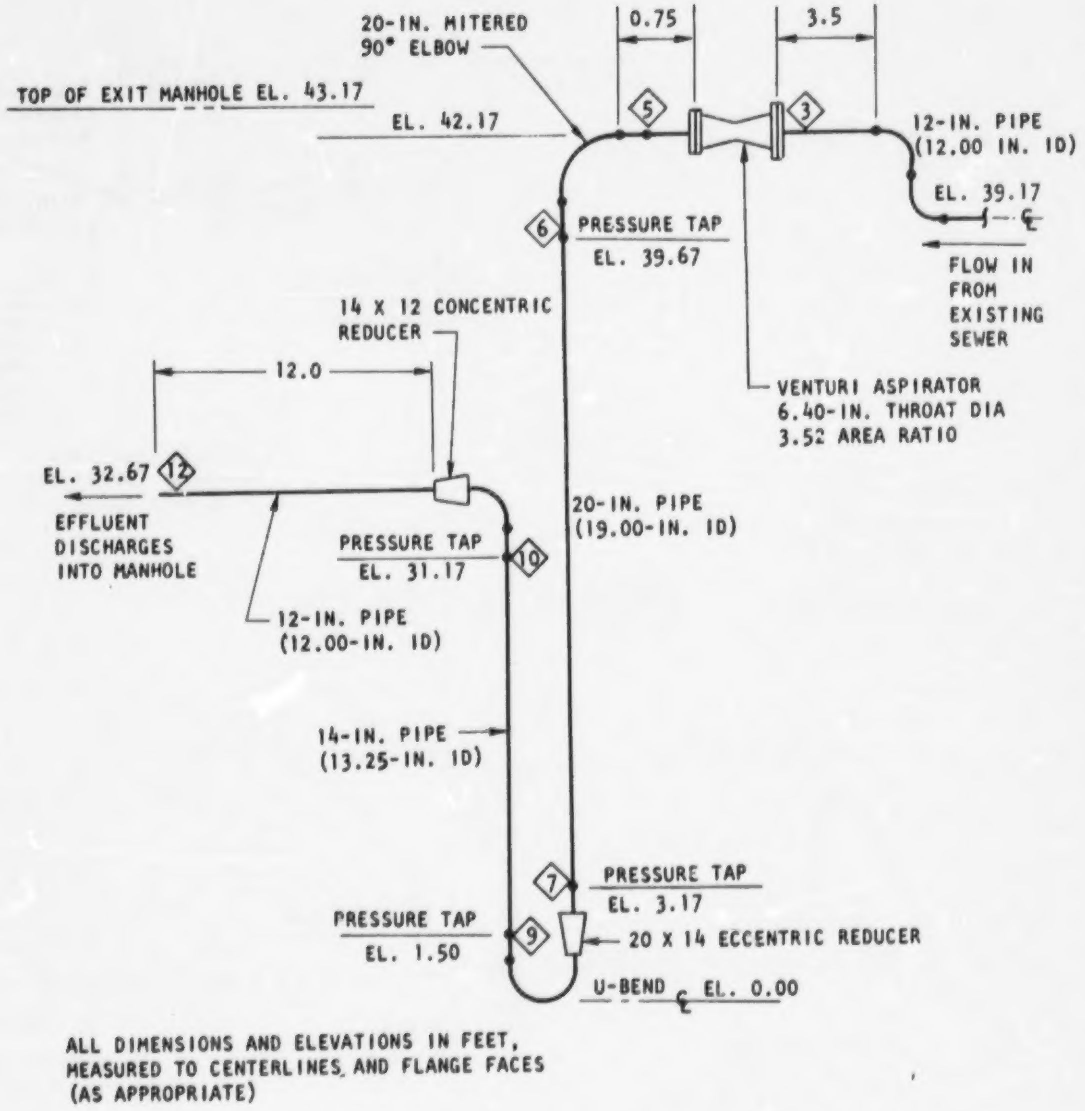

20-IN. MITERED 90° ELBOW
0.75
3.5
TOP OF EXIT MANHOLE EL. 43.17
EL. 42.17
5
3
12-IN. PIPE (12.00 IN. ID)
EL. 39.17
6
PRESSURE TAP
EL. 39.67
FLOW IN FROM EXISTING SEWER
14 X 12 CONCENTRIC REDUCER
12.0
VENTURI ASPIRATOR 6.40-IN. THROAT DIA 3.52 AREA RATIO
EL. 32.67
12
EFFLUENT DISCHARGES INTO MANHOLE
20-IN. PIPE (19.00-IN. ID)
PRESSURE TAP
EL. 31.17
10
12-IN. PIPE (12.00-IN. ID)
14-IN. PIPE (13.25-IN. ID)
7
PRESSURE TAP
EL. 3.17
PRESSURE TAP
EL. 1.50
9
20 X 14 ECCENTRIC REDUCER
U-BEND ℄ EL. 0.00
ALL DIMENSIONS AND ELEVATIONS IN FEET, MEASURED TO CENTERLINES AND FLANGE FACES (AS APPROPRIATE)

Figure 18. U-Tube System at Location 5, Jefferson Parish, Louisiana

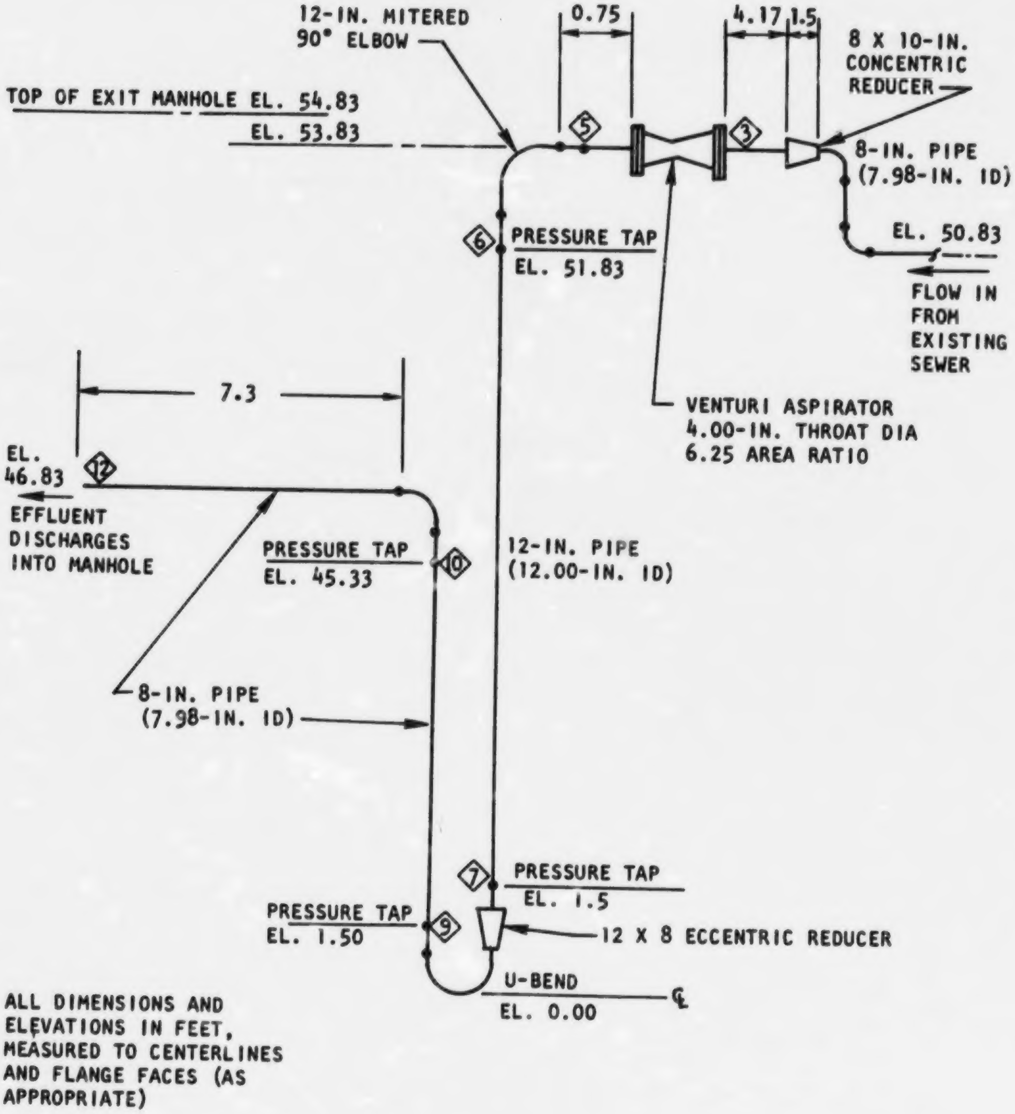

12-IN. MITERED 90° ELBOW
0.75
4.17
1.5
8 X 10-IN. CONCENTRIC REDUCER
TOP OF EXIT MANHOLE EL. 54.83
EL. 53.83
5
3
8-IN. PIPE (7.98-IN. ID)
6
PRESSURE TAP EL. 51.83
EL. 50.83
FLOW IN FROM EXISTING SEWER
7.3
VENTURI ASPIRATOR 4.00-IN. THROAT DIA 6.25 AREA RATIO
EL. 46.83
12
EFFLUENT DISCHARGES INTO MANHOLE
PRESSURE TAP EL. 45.33
10
12-IN. PIPE (12.00-IN. ID)
8-IN. PIPE (7.98-IN. ID)
7
PRESSURE TAP EL. 1.5
PRESSURE TAP EL. 1.50
9
12 X 8 ECCENTRIC REDUCER
U-BEND EL. 0.00
℄
ALL DIMENSIONS AND ELEVATIONS IN FEET, MEASURED TO CENTERLINES AND FLANGE FACES (AS APPROPRIATE)

Figure 19. U-Tube System at Location 7, Jefferson Parish, Louisiana

diameters (venturi throat, down-leg, and up-leg) were selected based on the average flowrate encountered at each location and optimized using the first-generation design computer program. The U-tube discharge point was positioned as low as possible in the manhole. This not only reduced the total head loss across the system but also reduced the amount of H_2S stripping in the exit manhole.

The method of aeration can be understood by following the flow of waste water through the U-tube. As the sewage leaves the force main and enters the throat area of the venturi, the velocity increases, thereby decreasing the pressure at the throat to below atmospheric pressure at the throat to below atmospheric pressure. This creates a pressure differential favorable to aspiration of air into the stream. The turbulent flow downstream of the venturi promotes mixing of the sewage and aspirated air. The down-leg acts as reactor in the sense that it provides retention time and the increased pressure as a function of depth, both of which enhance oxygen transfer from the entrained air bubbles to the sewage. The stream proceeds up the up-leg, aided by an air lift effect, and discharges into the manhole with an increased dissolved oxygen level. This prevents septic conditions from developing for a considerable distance downstream.

Test Procedure and Results

Experimental test procedures for evaluating these U-tube installations which involve force mains required that personnel be assigned to the pump station as well as the U-tube installation. Personnel at the pump station (constantly in contact with U-tube personnel via two-way radio communications) were responsible for manual operation of the pump cycles, recording both the pump discharge pressures, and the wet well levels. Concurrently, personnel at the U-tube installation were required to perform the necessary functions, e.g., setting air flowrates, measuring and recording pressures for selected points in the U-tube installation, and also sampling the stream and analyzing for dissolved oxygen (D.O.). Instrumentation of the U-tube installation consisted of a water manometer (seven tubes manifolded together), differential pressure gages, air compressor (for supercharging), air flowmeter, plus chemicals and apparatus for on-site determination of D.O. Figure 20 shows the typical test setup at location 7.

The typical test run consisted of the following sequence of events: (1) the water flowrate was set (this was accomplished by having either one or two pumps on line); (2) the desired air flowrate was set; (3) after the water and air flows were stabilized, pump discharge pressure, wet well levels, and air flowrate were measured and recorded; (4) pressures at stations 3, 5, 6, 7, 9, and 10 in the U-tube were measured and recorded; (5) the stream was sampled at stations 3 (upstream of the aspirator) and 12 (at the U-tube discharge point); and (6) the samples were analyzed for D.O. on site.

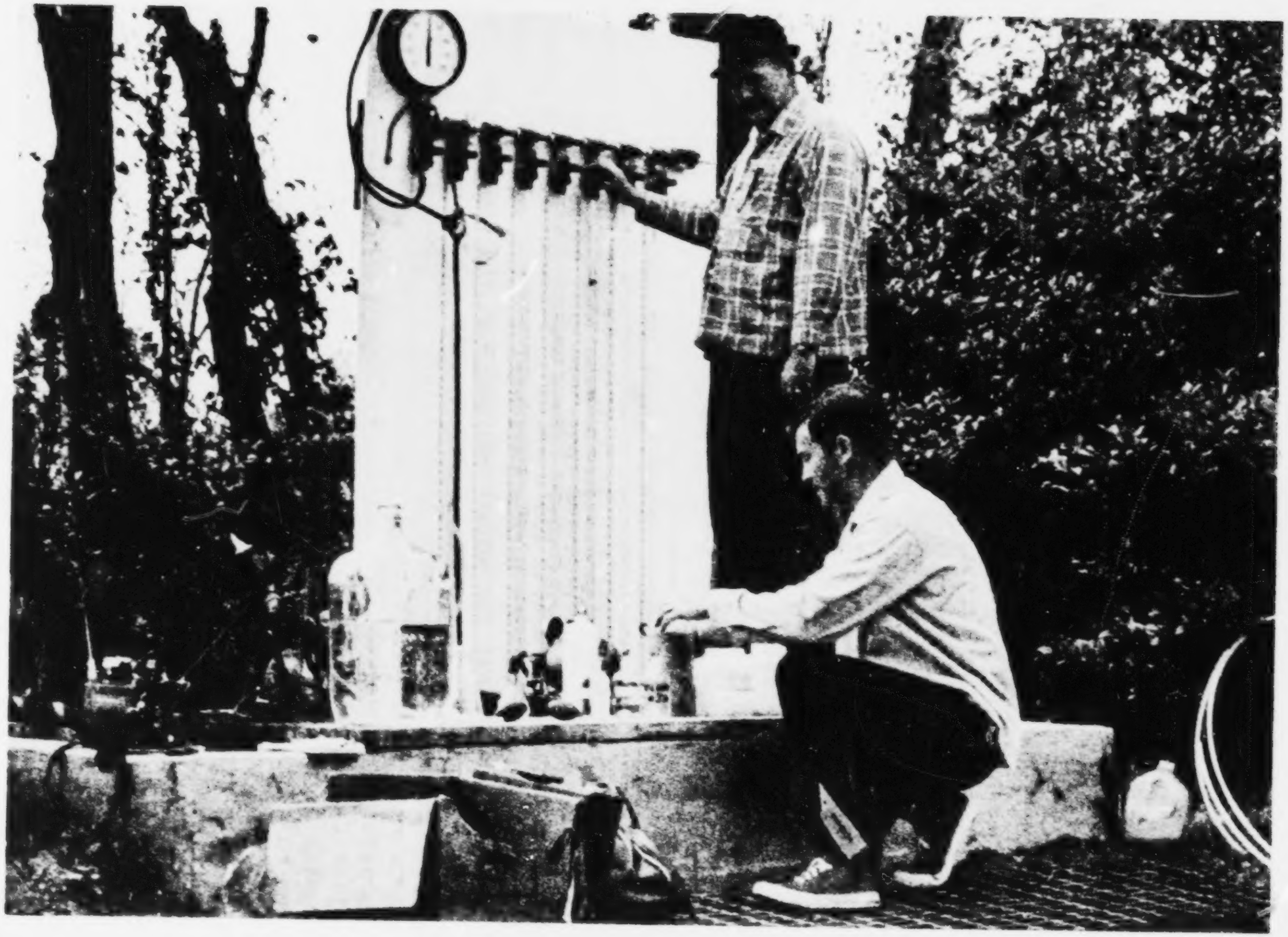


Figure 20. Field Testing at Location 7, Jefferson Parish, Louisiana

Variation of the water flowrates was limited because the only method of control was by using one lift pump for low flow or both lift pumps simultaneously for high flow. This had to be controlled manually at the pump station because, in normal operation, the pump cycles are automatic and alternate from one pump to the other unless there is an unusually high wet well level, in which case both pumps automatically come on line. Water flowrates were determined by reference to the discharge pressure read on 0- to 60-psi gages mounted on each pump discharge line. The discharge pressures were correlated to flowrates by making a series of runs without air aspiration and measuring the pressure drop across the venturi (which had been calibrated by the manufacturer). From these data, a plot was constructed that correlated pump discharge pressures to water flowrates whether or not air was being aspirated.

Air flowrate measurements were obtained by use of an integrating-type volumetric gas meter attached to the venturi aspiration jacket with a 2-inch line, and, in some tests by use of a rotameter. Regulation of selected air flowrates was accomplished by means of a throttling valve located upstream of the flowmeter. For air flowrates above maximum aspiration rates, a high-capacity, low-pressure compressor was utilized. Variation of supercharging flowrates was accomplished by running the compressor at full capacity and setting the by-pass valve (vent to atmosphere) to attain the desired flowrate. This procedure worked successfully at location 5. However, at location 7, supercharging raised the pump head to its cutoff point and thus precluded measurements in this regime.

Pressure measurements were obtained at various points along the U-tube using the manometer board. It can be seen (Fig. 20) that the seven tubes (attached to stations 3, 4, 5, 6, 7, 9, and 10) are connected to a manifold with isolation valves. During head measurements, a pressure (either positive or negative) was set on the manifold such that the water column would be on scale when the isolation valve was opened. After equilibrium was reached, both the pressure on the manifold as read on a differential pressure gage and the height of the water column were measured and recorded. This procedure was repeated for each station along the U-tube.

At location 5, a rather comprehensive set of hydraulic and oxygen transfer data was obtained. The variations in water and air flowrates provided 17 different A/W ratios, ranging from 0.02 to 0.79. In addition, a number of runs were conducted without air aspiration for flowrate calibrations and head loss measurements. However, at location 7, pump capacity was substantially lower and only three different A/W ratios (ranging from 0.04 to 0.20) could be obtained by aspiration. And, as previously mentioned, runs with supercharging were not possible. A summary of all data obtained from these locations is contained in Appendix B.

PORT ARTHUR

Application Sites

Port Arthur, Texas, located in southeastern Texas on the shore of Sabine Lake, is typical of many cities along the Gulf Coast in terms of the difficulty of preventing anaerobic conditions from developing in sewer lines. The city is essentially at sea level, the terrain is very flat, and the temperatures are relatively warm. Under EPA Grant 11010 DYO, the City of Port Arthur installed a number of aeration and oxygenation systems at selected points in its sewer system. Their purpose is twofold: to reduce the degree and extent of anaerobic conditions in sections of the sewer system, and to provide information about the practical operating characteristics and relative advantages of various devices for introducing oxygen into the waste water (one employing a pair of U-tubes, two pressurized aeration tanks, and two force mains) and three cryogenic oxygen injection installations (one using a U-tube, one force main with a diffuser, and one force main without a diffuser). The U-tube aerators are located at Pioneer Park lift station and Lake Charles lift station. The Pioneer Park lift station, which contains a compressed-air U-tube in line with each of the two parallel pumps used in alternate cycles, was selected as the field test site under this program. This U-tube station had been instrumented previously for testing under EPA Grant 11010 DYO. Considerable sulfide attack had become apparent in the 30-inch concrete gravity line downstream of this station, and it was necessary to replace it in September 1971, after the unusually short life of 20 years. Examples of the severe corrosion can be seen in Fig. 21 through 24.

Designs

The basic design approach was similar to that used for the Jefferson Parish installations, although the designs were prepared primarily by the Environmental Protection Agency, the City of Port Arthur, and the city's consultants, making use of parametric design information provided by Rocketdyne. The physical characteristics inherent in these sites dictated the desirability of using compressed-air U-tubes rather than aspirated-air U-tubes. With this basic premise, parametric design calculations were made with the design program developed previously from the pilot-scale data, considering the physical constraints of the particular application sites.

At the Pioneer Park lift station location (which is the case to which the following details apply), the lift pumps are located in a large, dry well adjacent to the wet well from which the pumps take their suction flow. There was ample space in the dry well to install the additional piping needed for a U-tube. Therefore, it was relatively simple to make this installation by splicing between the pump discharge line and the exit line which goes to a manhole from which the 30-inch gravity main flows. This lift station has a nominal flow capacity of 1400 gpm. The station

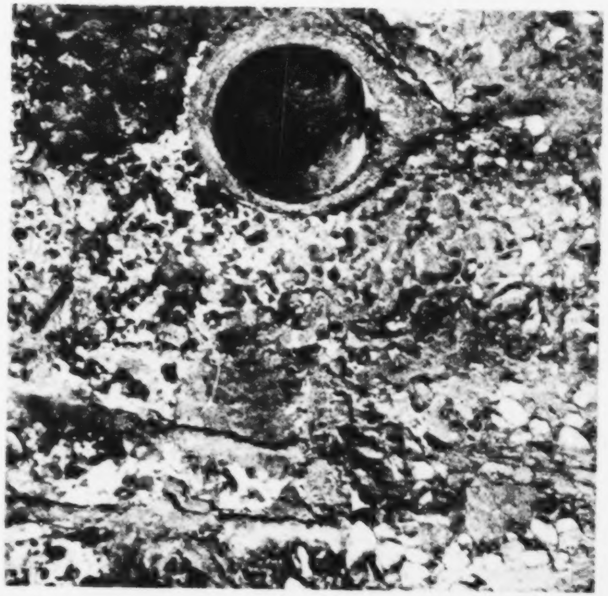


Figure 21. Pioneer Park Lift Station Discharge Box (Showing the 8-inch discharge line, and severe damage to concrete walls of the box; exposed large aggregate and reinforcing bars were originally covered with approximately 4 inches of concrete)

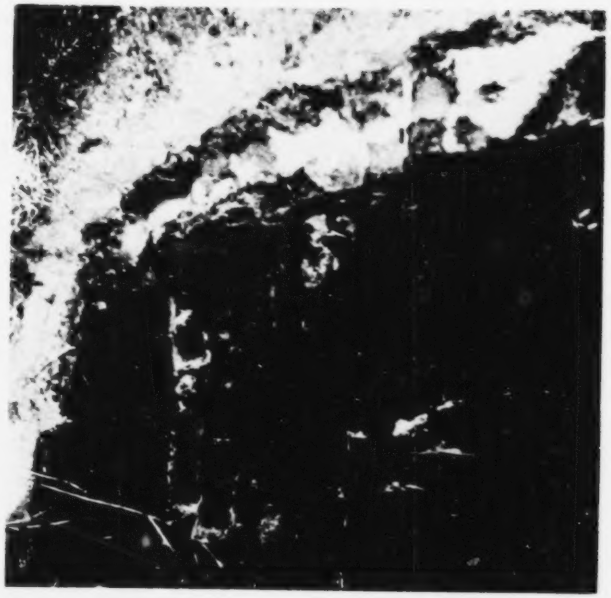


Figure 22. Manhole Downstream of Pioneer Park Lift Station (Manhole collapsed as a result of severe H_2S attack; mortar has been stripped from brick work)

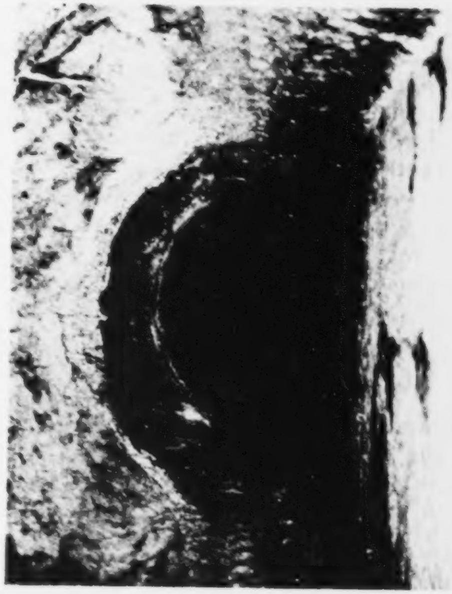


Figure 23. Gravity Line Downstream of Pioneer Park Lift Station (Complete deterioration of the gravity line; top portion shows rings of concrete that had joined sections of concrete gravity line. In some sections, the line has been completely eaten away by H_2S attack, leaving only dirt, as shown in this photograph)

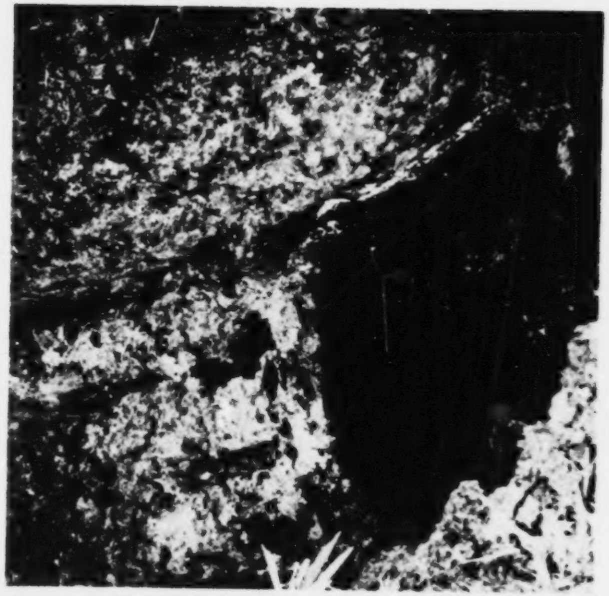


Figure 24. Gravity Line Downstream of Pioneer Park Lift Station (A section of gravity line, seen in preceding photograph, as viewed from above ground. The concrete joint ring remains; however, the top section of gravity line failed completely)

was ideally suited for a compressed-air injection system because of the on-site availability of electrical power to run the compressor and required solenoid valves.

The final U-tube installation and associated piping at the pump discharge is presented in Fig. 25. Only one of the two parallel systems is shown for clarity. It can be seen that the pump discharge stream travels up through an 8-inch line, through the electromagnetic flowmeter, and across to the top of the U-tube down-leg. At this point, the stream is expanded to an 18-inch down-leg, with an air-injection collar located at the top. Here, compressed air was forced into the stream through 32, 1/8-inch-diameter holes uniformly spaced around the circumference of the line. The stream proceeds downward at a reduced velocity and continually increasing pressure. These factors are important for efficient oxygen transfer from the entrained air bubbles. The stream then passes through an 18- by 12-inch reducer, travels around the U-bend, up the 12-inch up-leg at increased velocity (and aided by the lift provided by entrained air), and finally is discharged through an 8-inch line into the discharge manhole supplying a gravity main. Since this was to be an experimental aeration station, the U-tube was fitted with taps which allowed for pressure measurements and/or sampling of the stream, as shown in Fig. 25.

Test Procedure and Results

For efficient experimental evaluation of this installation, personnel were stationed on the lower level (pump and flow control), intermediate level (air injection control and monitoring), and upper level (supplemental controls, instrumentation readout, chemical analysis). The following sequence of events took place during each experimental run: (1) the water flowrate was adjusted to the desired level using a gate valve downstream of the pump; (2) the air injection flowrate was set, then measured with an in-line rotometer; (3) the water flowrate was measured with a Brooks Model 7108 electromagnetic flowmeter; (4) the pump discharge pressure was measured using a pressure gage; (5) the head loss measurements were conducted at stations 1, 4, 6, 7, 9, and 10 (Fig. 25) using a water manometer; and (6) water samples were drawn from stations 1 and 10 and analyzed on site for IDOD (initial oxygen demand) and D.O. using the Modified Winkler test. Periodically, water samples were analyzed for sulfide concentration.

Using this procedure, a matrix of tests was conducted in which water flowrates were varied from 400 to 1400 gpm, while the air flowrates were varied from 0 to 14 cfm. From these tests, oxygen transfer and pressure drop data were obtained for 18 different air-to-water ratios (y) ranging from 0.01 to 0.19. The complete data are given in Appendix B.

In each test, water samples were drawn from upstream of the air injector (station 1) and at the top of the up-leg (station 10). A 15-minute IDOD test was performed on the influent and effluent samples (the influent D.O. level was always zero); the IDOD and D.O. tests were performed on effluent.

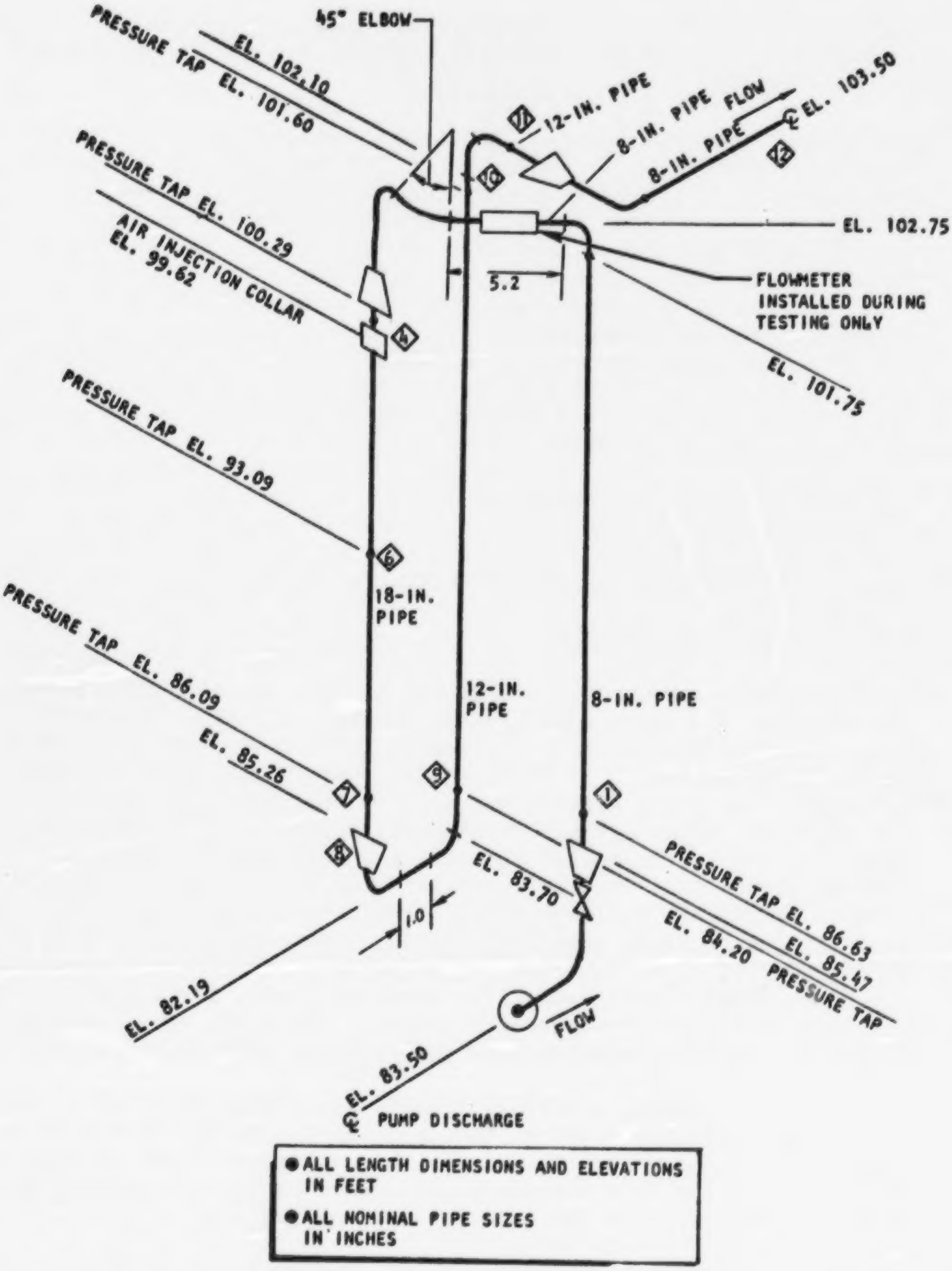

45° ELBOW
PRESSURE TAP EL. 101.60
EL. 102.10
PRESSURE TAP EL. 100.29
AIR INJECTION COLLAR EL. 99.62
12-IN. PIPE
8-IN. PIPE
FLOW
8-IN. PIPE
EL. 103.50
EL. 102.75
5.2
FLOWMETER INSTALLED DURING TESTING ONLY
EL. 101.75
PRESSURE TAP EL. 93.09
18-IN. PIPE
12-IN. PIPE
8-IN. PIPE
PRESSURE TAP EL. 86.09
EL. 85.26
EL. 83.70
1.0
EL. 82.19
PRESSURE TAP EL. 86.63
EL. 85.47
EL. 84.20 PRESSURE TAP
EL. 83.50
FLOW
PUMP DISCHARGE
ALL LENGTH DIMENSIONS AND ELEVATIONS IN FEET
ALL NOMINAL PIPE SIZES IN INCHES

Figure 25. U-Tube System Tested at Pioneer Park Lift Station, Port Arthur, Texas

These values were then used to calculate the oxygen transfer which actually occurred in the U-tube by the relation:

total oxygen transfer = IDOD (in) - IDOD (out) + D.O. (out)

To further evaluate the desirability of U-tube aeration of sewage, determinations of total sulfides were made for influent and effluent samples collected from five different runs. The results (presented in Appendix B) show substantial decreases in sulfide concentration from 25 to 87 percent. The hydraulic characteristics of this U-tube installation also were investigated by measurement of the pressure at the selected points. Pressure measurements were obtained using an open end water manometer which was manifolded to each of the test points. Data were obtained for each of the six U-tube test stations in each of 29 runs. This provided detailed characterization of head loss through the system.

SECTION VII

DATA ANALYSIS

The basic elements of a U-tube aeration system are: (1) a unit for introducing air (or oxygen) into a flowing water stream, followed by (2) two connected vertical conduits through which the air-water mixture flows down and back up, thus giving a substantial residence time in a region of above-ambient pressure. The device for introducing air could be one of several types of aspirators (in which air is induced by a local high-velocity, low-pressure region in the flowing water stream), or the device could be some type of diffuser through which compressed air is injected.

In addition to the type of device for introducing air, there are numerous variations in configuration, relative sizes of system components, and operating conditions that may be considered for each type. This variety of possibilities, and the complexity of the physical processes occurring within a U-tube system, makes it not satisfactory to present the experimental results in terms of graphs or equations giving overall oxygen transfer for various combinations of U-tube geometry, size, and operating variables. Similarly, the widely used "figure-of-merit"--weight of oxygen transferred per unit of power expended (e.g., lb oxygen/hp-hr)--can be very misleading if used to compare different types of aeration systems, since amortized capital costs and other expenses also can be very significant.

The primary goal of the data analysis performed was to develop a general design basis for predicting mass transfer and pressure loss characteristics for various U-tube systems under wide ranges of operating conditions. Since this report summarizes the results of two projects, performed in sequence, there was an evolutionary process with respect to the various steps of experimental testing, data analysis, design, etc. Data from the pilot-scale U-tube tests were used to calculate mass transfer coefficients and to develop an initial design program. This computer program was used to establish design conditions for the full-scale U-tube systems constructed. The data from tests with these full-scale systems were then used, together with the pilot-scale data, to improve the pressure drop and mass transfer correlations. The new correlations were incorporated into an improved data reduction program to calculate mass transfer coefficients. Then, the mass transfer coefficients were calculated as a function of pertinent parameters which would be known in a prospective design situation. Finally, the best available components drawn from this series of developments were combined into an improved U-tube design computer program, which is described in Section VIII of this report. The remainder of this section describes the data analysis and correlations which were developed for use in design.

PRESSURE LOSS CORRELATIONS

Discussed below are the relationships developed to predict pressure loss characteristics in venturi aspirators and in the two vertical sections

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(down-leg and up-leg) of a U-tube system. Use was made of available theory and data from the literature, where possible, in addition to the experimental results of this project.

Venturi Aspirator Pressure Loss

Equations were developed to predict the pressure loss across a venturi aspirator. These were based on the one- and two-phase data generated during this project, plus applicable data and information found in the literature.

Characterization of the pressure loss across a venturi with single-phase liquid flow is straightforward and the loss can be correlated easily as a function of the water velocity and the throat-to-inlet-diameter ratio for a given type of venturi contour. However, when air is injected into a flowing water stream at the throat of a venturi, the interactions of the air and water create a complicated flow pattern that is intractable to analysis except on an overall basis.

A complete theoretical treatment of the pressure losses in a venturi aspirator would have to consider all sources of energy losses, including:

1. Boundary layer (friction) losses
2. Gas-liquid interfacial friction losses
3. Losses due to momentum exchange in the mixing region
4. Losses due to compressing the gas from the inlet throat pressure to the exit pressure

The gas-liquid interfacial friction loss cannot be evaluated theoretically. This loss would be a function of bubble size and shape distribution, velocities of liquid and air bubbles, and the physical properties of both air and water. The bubble size would be affected by the geometry and size of the injection manifold plus the flowrates of air and water. An estimate could be made of the loss due to momentum exchange; however, it would be necessary to make gross assumptions concerning the shape of the interface between the water and the air-water mixture downstream of the air inlet. The pressure loss due to the compression of the gas can be estimated from the ideal gas law assuming isothermal compression. This loss can be significant when the pressure ratio of the aspirator is high due to a large contraction area ratio; however, it would normally be less than 5 to 10 percent of the total pressure drop across an aspirator. Part of the compression loss is recovered later in the system as the pressure decreases.

The initial efforts in developing an equation to predict venturi aspirator pressure loss involved an approximate theoretical analysis. Comparison of these initial theoretical predictions with the pilot-scale data showed considerable discrepancies in some regions. Since it was beyond the scope of the project to develop the theoretical analysis further, it was decided to modify it and develop a semi-empirical correlation. Two correlations were developed: one for the pilot-scale data (which represents a conventional conical entrance and diffuser venturi contour), and one for the full-scale data (which are for a shortened, more complex curvature type of venturi contour). Combining the data for the two different types of aspirators would have led to unsatisfactory behavior of the correlation.

One unexpected, and disappointing, observation was apparent from the field data for the full-scale aspirators. These venturies were originally selected because their weight, length, and cost were much lower than for conventional conical venturies in the large sizes involved (12- and 8-inch pipe), and also the manufacturer's information specified that the one-phase pressure losses were even lower than those for a conventional venturi (about 10 percent of the entrance to throat pressure difference for the contraction ratios used in Jefferson Parish). However, the observed pressure losses with water alone flowing averaged about 39 and 26 percent of the entrance-to-throat differential for the venturies at Jefferson Parish locations 5 and 7, respectively. These are much higher than both the manufacturer's specifications and the observed losses in the pilot-scale conventional venturi (for which the corresponding average loss was about 17 percent). The reasons for the high single-phase losses of the aspirators used in Jefferson Parish are not known.

Pilot-Scale Aspirator. The aspirator pressure loss data obtained for the pilot-scale aspirator (2.07-inch pipe ID, area ratio of 8) are shown in Fig. 26. The single-phase pressure drops varied between 16 and 20 percent of the total throat velocity head, with an average of 17.6 percent. This agrees well with the predicted single-phase head loss for typical Herschel venturies (10 to 20 percent of the pressure difference between the inlet and throat) and indicates normal conditions during the runs.

The experimental data were analyzed using a least squares computer program, and a semi-empirical correlation was developed:

$$\Delta p = 0.00191\ (y)^{0.901}\ (u_{th})^{3.122} + 0.00246(u_{th})^2 \qquad (1)$$

The pressure drop, Δp, is expressed in feet of water, u_{th} is the superficial water throat velocity, in ft/sec, and y is the air-water volume ratio at 68°F and 13.8 psia. The correlation predicts that the pressure drop is approximately linear with respect to y. This is also apparent from the trends of the experimental pressure loss data in Fig. 26. Also shown in Fig. 26 are parametric curves generated from the correlation equation at throat velocities of 11.9, 15.3, 19.1, 23.0, and 27.6 ft/sec.

A search of the literature uncovered only two other sets of data on venturi aspirators. Jackson's data (Ref. 17 and 18) are for two venturi

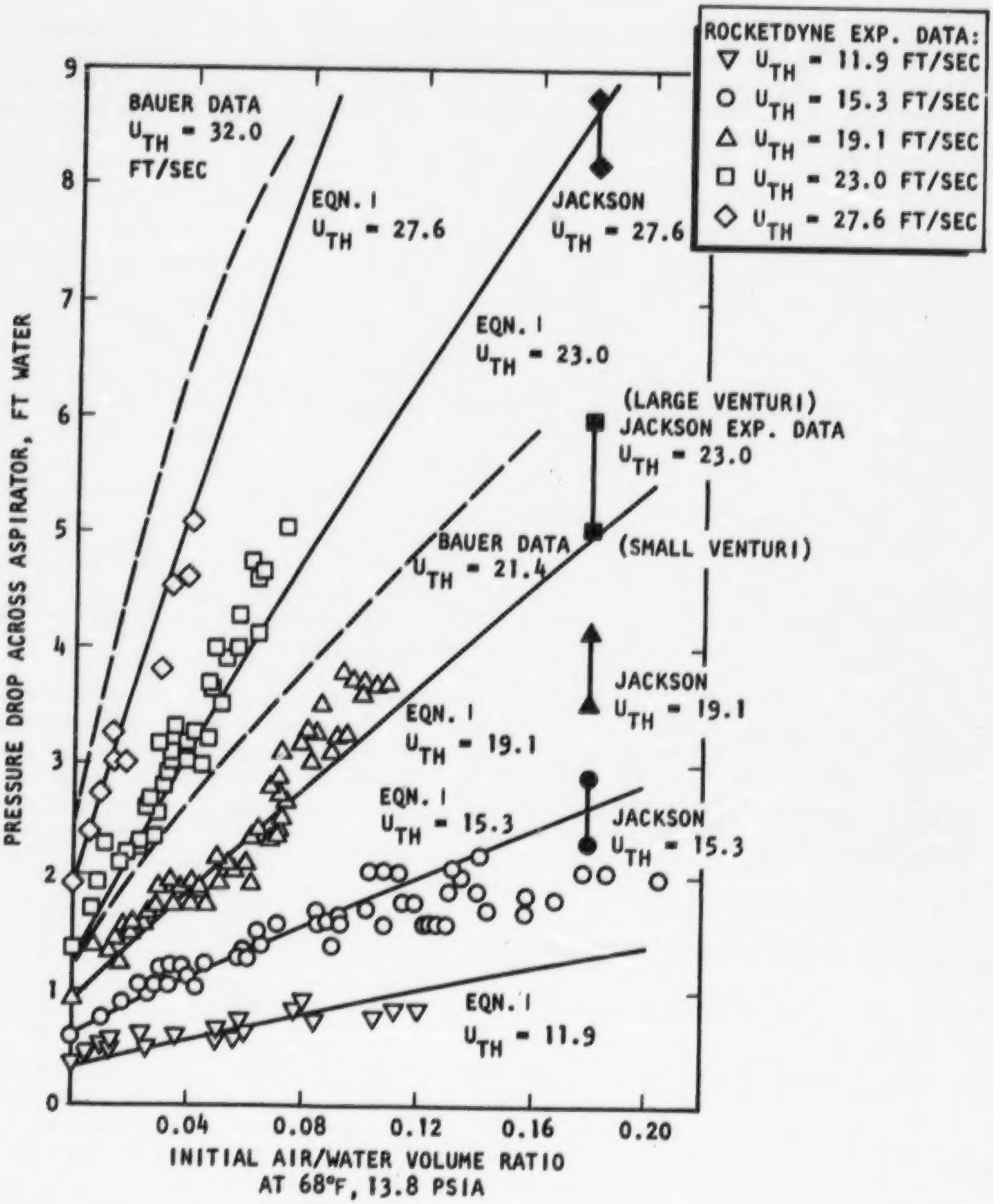

Figure 26. Two-Phase Pressure Drop Across Pilot-Scale Venturi Aspirators

sizes and with air and water. Bauer's data (Ref. 19) are for carbon dioxide and water, but should still be comparable, assuming that no large amount of carbon dioxide was dissolved within the actual venturi (since the venturi was rather small, this is probably not a bad assumption). These additional data also are plotted in Fig. 26. The data could not be plotted directly since neither the throat velocity nor the air-to-water ratio were held constant. The data were first plotted as a function of throat velocity, since the gas-to-water ratios were nearly constant. A slight arbitrary adjustment of the resulting curves to account for the small changes in y gave curves from which pressure loss could be read as a function of throat velocity for constant y. Values were read from this intermediate curve and plotted in Fig. 26 for comparison with the experimental data obtained during this project.

The Bauer data show good agreement with the curves generated from Eq. 1 for both throat velocities tested (21.4 and 32.0 ft/sec). The Jackson data show excellent agreement at u_{th} = 15.3 ft/sec, but the other six Jackson data points show pressure drops considerably lower than those computed from Eq. 1 at the higher throat velocities. The reason for these differences is not known, but may be due to differences in geometry and details of the air injection ports.

Full-Scale Venturi Aspirator. Only the data for the venturi aspirator at Jefferson Parish location 5 (12.00-inch pipe ID, 3.52 area ratio) were used in developing the correlation since there were only a small number of valid data points for the aspirator at location 7. The single-phase pressure drops for the location 5 aspirator were all high relative to the manufacturer's specifications, indicating either errors in measurement or some unusual condition in the flow system that would account for the low head recovery. As discussed previously, a different form than Eq. 1 was found to be best for these data. The dependence on y was assumed to be linear and the final equation contains a quadratic function of u_{th} as the y coefficient:

$$\Delta p = (48.7538-7.8410u_{th}+0.3634u_{th}^2)y+0.007432u_{th}^2 \qquad (2)$$

With no air flow (y = 0), the high value of the u_{th} coefficient indicates the poor single-phase pressure recovery, as was shown by preliminary computations from the individual data points with no air flow.

The experimental data are shown approximately in Fig. 27, together with the pressure losses computed from Eq. 2 at three throat velocities. The experimental velocities were not all exactly equal to the three major values shown on the graph. The points labelled 15.3 ft/sec actually had throat velocities in the range 15.3 to 15.7 ft/sec. The points labelled 19.3 ft/sec had velocities ranging from 18.2 to 20.1 ft/sec. The actual velocity for each data point was used in developing the correlation.

Recommendation for Design. The predictions of Eq. 2 are unnecessarily pessimistic; it seems reasonable to expect that future development and testing of large-scale aspirators can result in much better pressure loss performance. Consequently, an equation was developed to represent the pilot-scale data combined with those of Ref. 17 and 18:

$$\Delta p = 0.004\ (y_o)^{0.6}(u_{th})^{2.6} + 0.0026(u_{th})^2 \tag{3}$$

where the pressure drop across the aspirator, Δp, is given in feet of water; y_o is the air-water volume ratio at the aspirator entrance, expressed at 68°F and 1 atm; and u_{th} is the single-phase or superficial water velocity at the throat, in ft/sec. Until more data are available from large venturi aspirators, it is recommended that Eq. 3 be used to predict pressure drops.

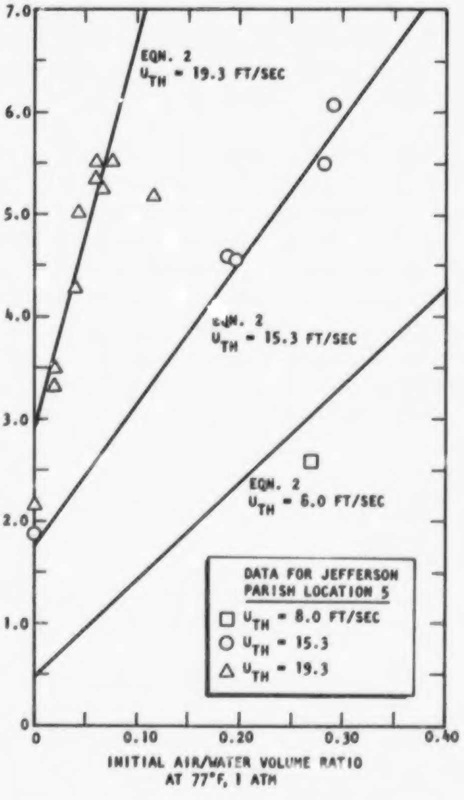

Figure 27. Two-Phase Pressure Drop Across Large Venturi Aspirators

Down-Leg Pressure Loss

A literature search located only limited references pertinent to the phenomenon of vertical downward two-phase flow. Unfortunately, all of the correlations which were presented pertained to slug flow or higher air-to-water ratio flow regimes. Extrapolation of empirical results across two-phase flow regime boundaries is meaningless. Therefore, it was necessary to develop a correlation for down-leg pressure drop with bubble flow from the U-tube data. Both the large-scale field data and the pilot-scale data were used.

Development of Correlation. For convenience in design usage, it was decided to correlate the data in terms of the mean head loss per foot, evaluated as follows. The starting point was the energy equation as it applies to the down-leg portion of a U-tube:

$$d\left(\frac{u^2}{2g_c}\right) + \frac{g}{g_c}\,dz + dG + \frac{dp}{\rho} = 0$$

where u is the velocity of the mixture in ft/sec, z is the height in the pipe in feet, g is the mechanical energy loss converted into heat in lbf-ft/lbm, p is the absolute pressure in lbf/ft^2, and ρ is the mixture density in lbm/ft^3. For this section of the pipe, the velocity can be considered constant. This, plus identifying the mechanical energy loss term with head loss (h_L) through the relation $dG = dh_L/\rho$, gives:

$$\frac{g}{g_c}dz + \frac{dp}{\rho} + \frac{dh_L}{\rho} = 0 \qquad (4)$$

To integrate Eq. 4, the behavior of h_L with respect to z must be known. The simple assumption that the head loss per foot is constant is consistent with the original purpose of defining a mean head loss per foot and, as will be seen later in this section, is upheld by the experimental data. With the postulate that dh_L/dz is a constant, i.e., -m (m is positive), Eq. 4 can be written as:

$$dp - m dz + \frac{g}{g_c}\rho dz = 0 \qquad (5)$$

Introducing the air-to-water volume ratio, y, and noting that the density of water, ρ_w, is much larger than the density of air, ρ_a, results in the relationship:

$$\rho = \frac{\rho_w}{1+y} + \frac{y\rho_a}{1+y} \simeq \frac{\rho_w}{1+y} \qquad (6)$$

Substituting Eq. 6 into 5 and converting the units of pressure to feet of water by dividing through by $g\rho_w/g_c$, leads to the following equation:

$$dp - mdz + \frac{1}{1+y}dz + 0 \qquad (7)$$

where p now has units of feet of water and m has units of feet of water per foot.

Under the assumption that y is inversely proportional to pressure (i.e., yp is constant, which neglects for this purpose the effect of gas absorption on down-leg pressure), Eq. 7 can be integrated along the down-leg of the U-tube to yield:

$$p_2 = p_1 - \frac{y_1p_1}{1-m} \ln \frac{(1-m)p_2 - my_1p_1}{(1-m)p_1 - my_1p_1} + (1-m)|z| \qquad (8)$$

where the subscripts 1 and 2 refer to the top and bottom of the down-leg, respectively.

Measurements were made of p_1, P_2, and z in the field as well as in the pilot scale testing program. The product y_1p_1 is known from the relation $y_1p_1 = y_oP_o$ where y_o and p_o are the initial injected air-to-water volume ratio and initial pressure, respectively. From this information, values of m can be determined from Eq. 8.

In one-phase flow, the parameter m is usually correlated in terms of the Fanning equation and friction factor. In that case, m would be a function of the velocity, u, the pipe diameter, D, and the fluid viscosity and density (through a Reynolds number effect). In the two-phase flow case, then, it might be expected that m would still be a function of these parameters as well as the air-to-water volume ratio.

Values of m were determined from the Rocketdyne pilot-scale data as well as the field data. The field data obtained from Jefferson Parish were not useful in this correlation. In many cases, slug flow was present, leading to enormous pressure drops. In several other cases, the data erroneously indicated that there was more pressure gain in the down-leg than could be accounted for by just the difference in elevation (i.e., $m<0$). It was decided to rely on the data obtained from the Port Arthur testing, together with the pilot-scale data, for use in developing the down-leg pressure loss correlation. The Port Arthur data were quite usable, except for runs 837 through 849 in which it was apparent that slug flow was dominating the loss mechanisms.

Table 4 summarizes the average values of m and 90-percent confidence intervals for m which were developed for the various sets of experimental data, assuming that the experimental data errors were all normally distributed.

TABLE 4. CONSTANTS FOR DOWN-LEG PRESSURE LOSS CORRELATION

Origin of Data	Distance Between Pressure Taps $\|z\|$, feet	Head Loss per Foot (m) With 90-Percent Confidence Interval, ft water/ft
Rocketdyne Pilot-Scale U-Tube	6.7	0.024 ±0.002
Rocketdyne Pilot-Scale U-Tube	16.6	0.020 ±0.002
Rocketdyne Pilot-Scale U-Tube	25.7	0.025 ±0.002
Rocketdyne Pilot-Scale U-Tube	34.3	0.028 ±0.004
Rocketdyne Pilot-Scale U-Tube	43.2	0.019 ±0.002
Rocketdyne Pilot-Scale U-Tube (all of above)	All Five Lengths	0.023 ±0.001
Port Arthur	7.0	0.023 ±0.005
All of Above	--	0.023 ±0.001

Equation 8 could also be applied to a small increment of length ($|z|$) in the down-leg, to calculate the pressure at the bottom of the increment (ρ_{i+1}) from the pressure at the top of the length increment (ρ_i). However, Eq. 8 is not very convenient for this purpose since it defines p_2 only implicitly. When the values of m were being determined from measured values of y_1, p_1, p_2, and $|z|$, Eq. 8 was solved exactly using Mueller's iteration scheme to find the root of this nonlinear equation. To avoid this unnecessary complexity when applying Eq. 8 to a small increment of length (for ρ_{i+1} close to ρ_i), Eq. 8 can be linearized by expanding the logarithmic terms in the series form:

$$\ell n\,(1+\delta) = \delta-\delta^2/2+\delta^3/3 \ldots$$

For small δ, $\ell n\,(1+\delta)\approx\delta$. If this is done, an explicit relation can be found for p_{i+1}, which is suitable for a small step in length (e.g., 0.1 ft):

$$p_{i+1} = p_i + \left(\frac{1}{1+y_i} - m\right)|z| \qquad (9)$$

Equation 9 can then be used to predict p_{i+1} from p_i and y_i and for small $|z|$ (i.e., small step sizes). This was done in the data reduction and design programs, using a value of m = 0.023.

Discussion of Down-Leg Pressure Loss Data and Correlation. Part of the experimental data are shown in Fig. 28, together with the corresponding predicted curves predicted from Eq. 8, using the values of m which best fit each set of data (m = 0.025 for the pilot-scale data with this length, and m = 0.023 for the Port Arthur data, as given in Table 4). There are a number of interesting observations which can be made from this graph, as well as from examination of trends in the other data not included in Fig. 28.

The data for the two U-tube systems with pipe diameters differing by almost an order of magnitude are essentially equivalent in terms of down-leg pressure change. The small differences between the two sets of data, and the two regression curves plotted in Fig. 28, are almost entirely due to a general difference in the absolute pressure range between the two cases. The absolute pressures at the top of the down-leg were typically about 48 ft water for the data at Port Arthur and about 32 ft water for the pilot-scale data. When this effect is taken into account, it can then be seen from Fig. 28 that, for y greater than ~0.025, there appears to be little or no other discernible difference between the Rocketdyne pilot-scale data and the Port Arthur data. This indicates that changing the diameter of the pipe has little effect, although this result runs contrary to what is experienced in one-phase flow. For y less than 0.025, there are larger differences between the losses for the two sets of data (Fig. 28), which is reasonable since the one-phase (i.e., y=0) losses are known to be a strong function of pipe diameter.

Another conclusion which can be drawn from the data (see Fig. 28) is that there appears to be essentially no dependence on water velocity. This is true even though the data cover about a threefold range of velocity.

Extensive analysis of all the data indicated not only the total pressure change per foot was independent of the pipe diameter and the fluid velocity (for y > 0.025), but for y > 0.025 the actual head loss per foot, m, was also independent of the air-to-water volume ratio, y. This result is consistent with the earlier assumption that the head loss per foot is constant, which was made to integrate Eq. 7.

For the purpose of this correlation, only those values of m for y > 0.025 were considered. This was large enough so that the two-phase losses were the controlling factor. Furthermore, to avoid slug flow regimes, almost all the m values analyzed had an associated y value of less than 0.15. This is why the regression curves presented in Fig. 28 are limited to this range on y. It should be noted that any possible lack of fit these curves have for their respective data is, in large part, due to the fact that all the pilot-scale and Port Arthur data were used to obtain the correlation. For clarity, only part of these data are shown in Fig. 28.

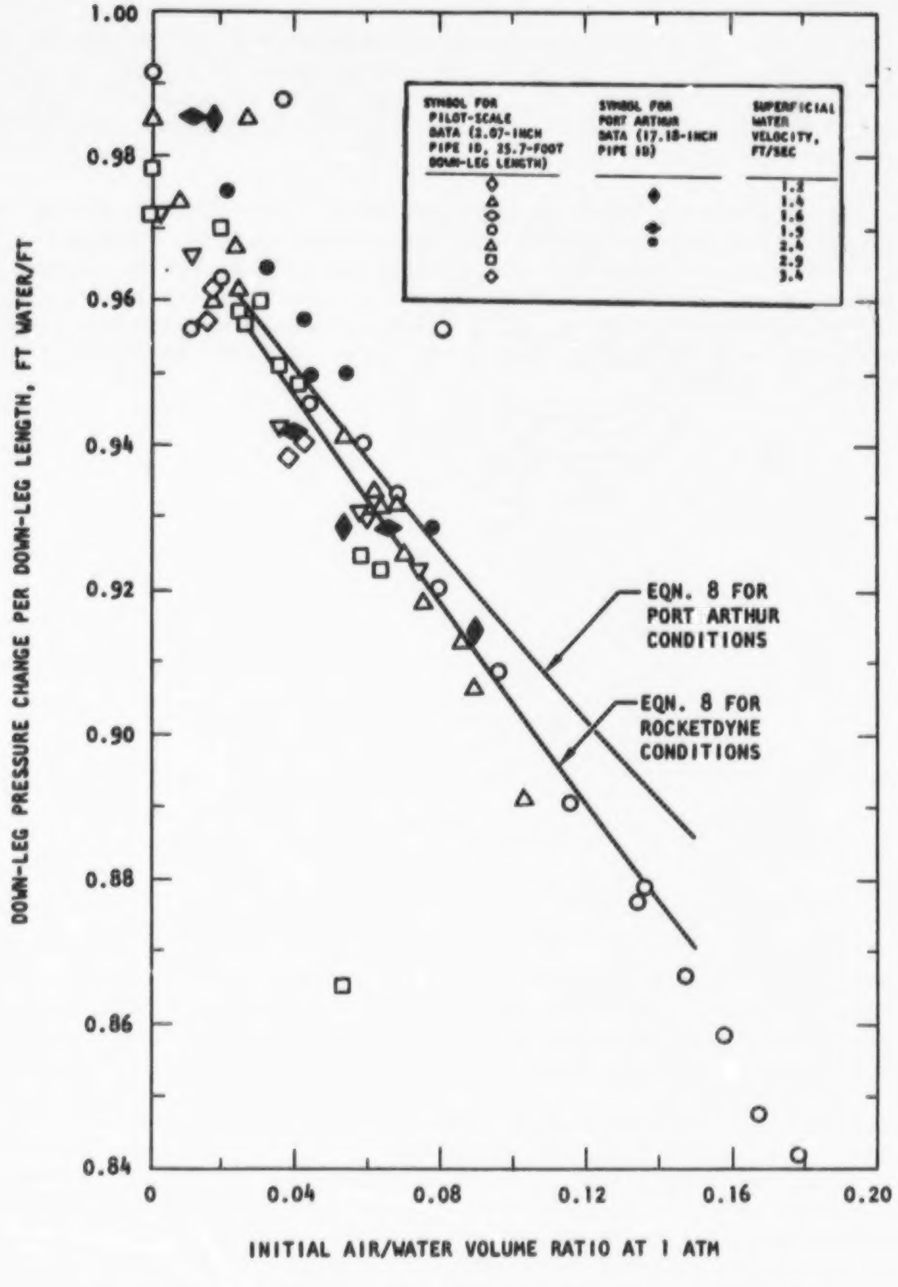

Figure 28. Experimental Down-Leg Pressure Change for Rocketdyne Pilot-Scale Data and Port Arthur Data

Up-Leg Pressure Loss

Up-leg pressure gradient measurements were made only for the 37-foot pilot-scale U-tube. The average pressure differential per foot, F, is presented in Fig. 29 as a function of air-to-water ratio at standard conditions. It should be noted that F also includes the static pressure change, for reasons which will be apparent below.

The data scatter is great enough that direct correlation of the data did not appear fruitful in predicting the up-leg pressure gradient. Therefore, the Hershey correlation for the prediction of pressure gradients in air-lift pumps was used (Ref. 20). It was judged that the correlation would be applicable to the up-leg of the U-tube, since similar two-phase flow conditions were involved. The correlation is (see the Glossary for definitions of symbols):

$$\frac{dp}{dL} = - \frac{\rho_w + 2\ f^*\ u_m^{\ 2}\ \rho_w / g_c D}{1 + y + \dfrac{\rho_w\ u_m}{g_c}\ \dfrac{du_m}{dp}} \qquad (10)$$

$$\frac{du_m}{dp} = \frac{4\ p_o\ u_a}{\pi\ D^2\ p^2}$$

$$f^* = 0.048(\mathrm{Re})^{-0.13}$$

$$\mathrm{Re} = \frac{D u_m\ \rho_w}{\mu_w}$$

$$y = 3.5\ (Q_s D^{-2.5} gc^{-0.5})^{0.83} \qquad (11)$$

$$Q_a = Q_s + y\ Q_w \qquad (12)$$

The term dp/dL is the pressure loss or recovery per foot at local conditions, including the static head. Under U-tube flow conditions, the denominator can be simplified to 1 + y since the derivative term is small. The solution for dp/dL requires solving Eq. 10 through 12 simultaneously.

Predictions of up-leg pressure change were made using the Hershey correlation to evaluate F at various depths in the column, and then integrating F to yield the total pressure differential across the up-leg. The two curves shown in Fig. 29 were generated by dividing these integrated results for total pressure change by the up-leg length. It is apparent that the 2 and 3 ft/sec water velocity curves bracket the bulk of the data. Many of the points below the band of the two curves appear to be erroneous; some are for water velocities below 2 ft/sec.

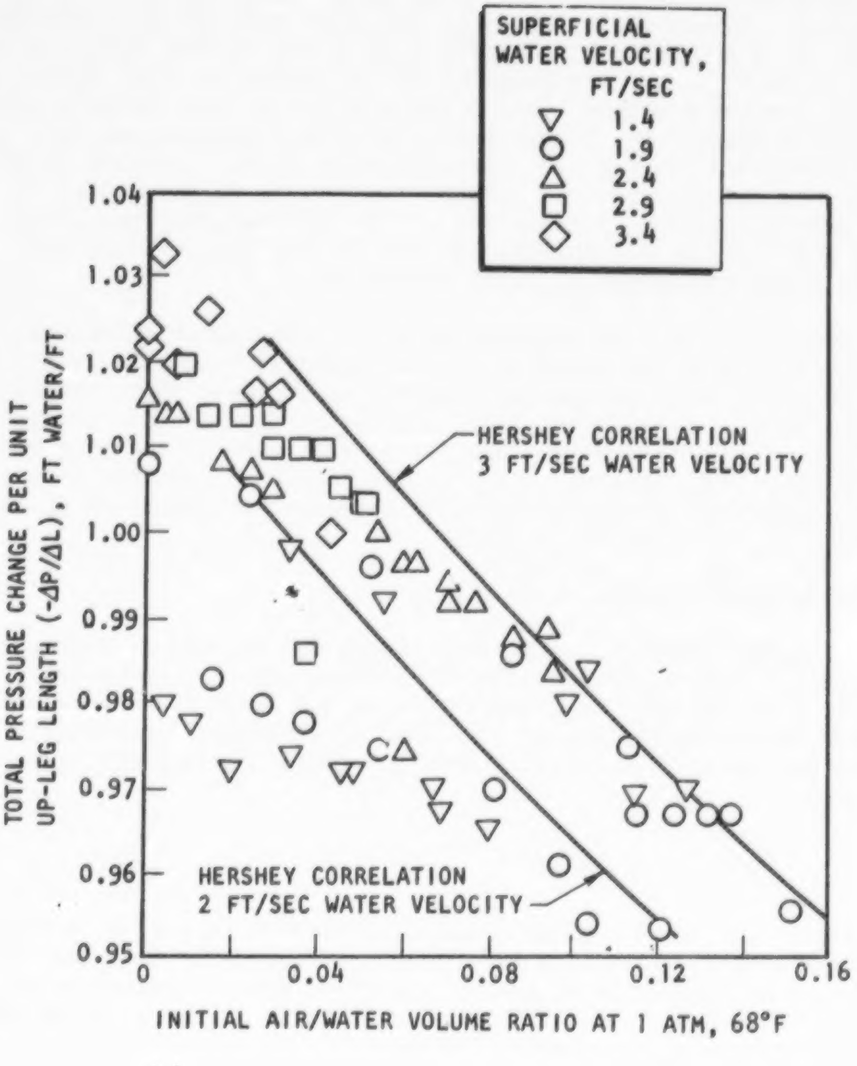

Figure 29. Experimental Up-Leg Pressure Change Data and Hershey Correlation

As a further check on the utility of the Hershey correlations, a comparison was made of the predictions with Adams' data for 4-inch diameter pipe (Ref. 21). Adams reports only the two-phase pressure loss effects. The single-phase loss for 4-inch steel pipe at 3.7 fps was estimated to be 0.012 ft water/ft and was added to his two-phase recovery data. This correction enabled a common basis of comparison between the data and the Hershey correlation. The integrated form of the equation was used to develop the curves shown in Fig. 30. Adams reports linear pressure recovery with respect to the air-to-water ratio. The Hershey Equation predicts deviation from linearity. For the 30- and 40-foot lengths, the curves agree up to about $y = 0.10$. For the 10- and 20-foot lengths, the two sets of curves begin to diverge at lower values of y.

In summary, the Hershey correlation predictions agree quite well with, but are slightly more conservative (i.e., predicted head loss is slightly higher) than, the experimental data for up-leg head loss obtained during this project. On the other hand, the Hershey correlation predictions begin to be less conservative than Adams' experimental data for air-to-water ratios above approximately 0.1. It was concluded that the Hershey correlation could and should be used for subsequent estimates of up-leg head loss.

ASPIRATOR MASS TRANSFER

Mass transfer coefficients were evaluated for the pilot-scale venturi aspirator from the experimental data obtained during this project. Corresponding data for the large aspirators in the field tests were not obtained because of the difficulty of obtaining water samples immediately downstream of the aspirators. Coefficients were defined by the basic transport equation:

$$\frac{dC}{dt} = K_L a \, (C_s - C) \qquad (13)$$

Where C is the local concentration of dissolved oxygen, t is time, "a" is the air-to-water interfacial area per unit volume of two-phase fluid, C_s is the local saturation value for dissolved oxygen concentration, and K_L is the liquid-phase mass transfer coefficient. Integration of the above equation, assuming constant C_s, gives

$$tK_L a = \ell n \left(\frac{C_s - C_4}{C_s - C_5}\right) \qquad (14)$$

where the subscripts 4 and 5 refer to the venturi throat and diffuser exit, respectively. The liquid residence time in the diffuser was taken as V/Q, where V is the diffuser volume and Q is the fluid volumetric

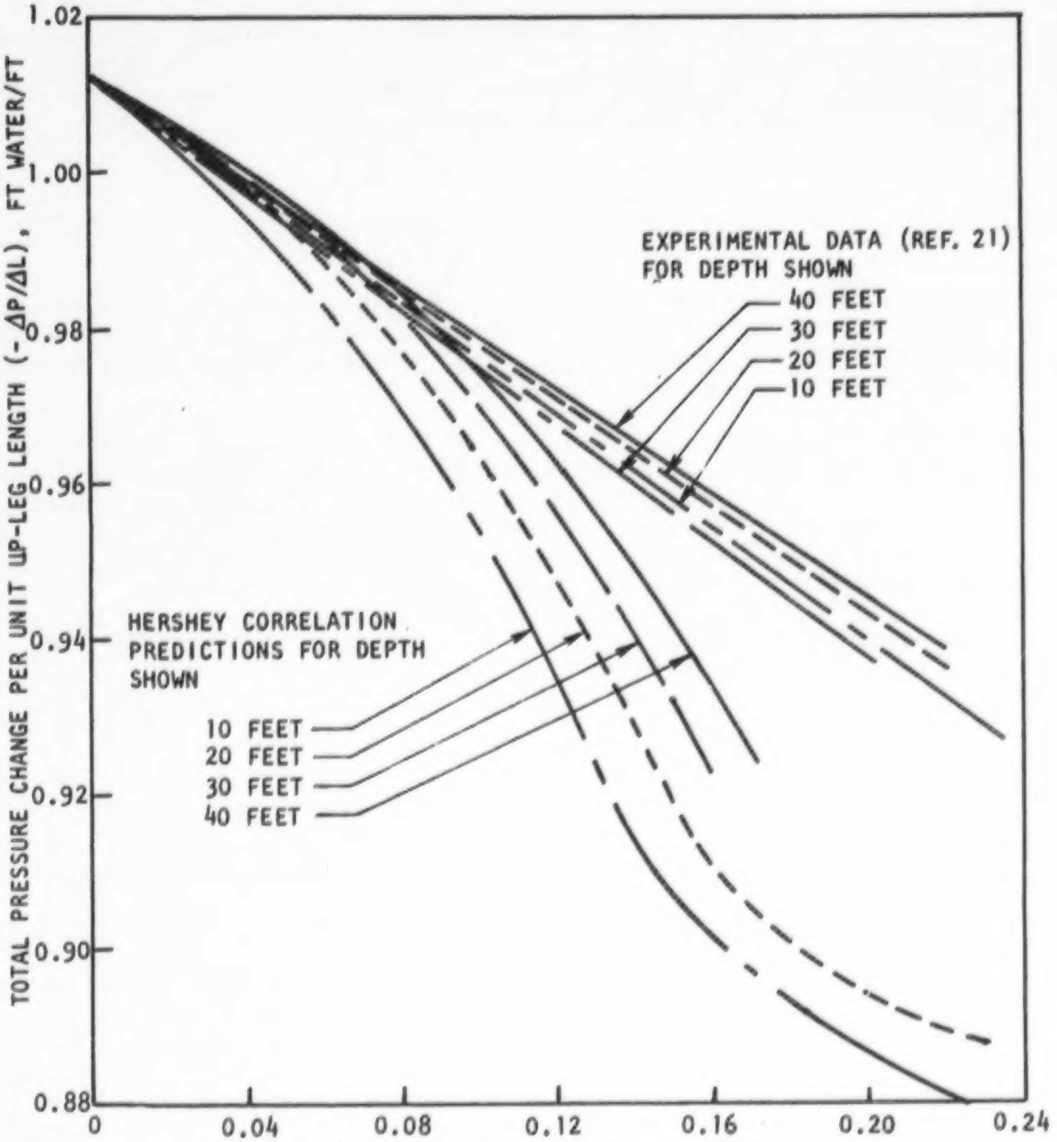

Figure 30. Adams' Experimental Up-Leg Pressure Change Data and Hershey Correlation

flow rate. C_4 and C_5 were measured venturi inlet and exit D.O. levels (Runs 139-219). With a specific assumption about how to evaluate a "mean" value of C_s (at some "mean" diffuser pressure), the overall mass transfer coefficient, K_La, was evaluated from the expression

$$K_La = \frac{Q}{V} \ \ell n \left(\frac{C_s - C_4}{C_s - C_5} \right) \tag{15}$$

No attempt was made to evaluate K_L alone since the effective mean value of "a" was not determinable. It was also not possible to separate the effects of oxygen transfer during bubble formation from transfer in the remainder of the aspirator diffuser.

Jackson concluded that the majority of the mass transfer occurred in his venturi aspirators after considerable pressure drop had been recovered (Ref. 17). Accordingly, C_s was evaluated at a pressure corresponding to 3/4 of the distance from the throat to the diffuser exit. It was shown that evaluating C_s half-way down the diffuser or at the diffuser exit shifted the calculated coefficients by less than ±6 percent. The dissolved oxygen saturation data of Montgomery (Ref. 22) were used, together with Henry's law to evaluate C_s at various temperatures and pressures. K_La was also corrected to 20°C by the expression:

$$\frac{(K_La)_{20}}{(K_La)_T} = (1.024)^{20-T} \tag{16}$$

where T is the experimental water temperature in degrees Centigrade.

The calculated coefficients are shown in Fig. 31 as a function of superficial water velocity, u_w, and air-to-water ratio, y. It is apparent that below $y = 0.04$ the scatter is severe, whereas above $y = 0.04$ the trend of K_La as a function of flow rate becomes readily discernible. The severe scatter below 0.04 is due to high percentage errors in both the air flow rate and the dissolved oxygen measurements at low air-to-water ratios. The resulting dependence of K_La upon y_o° (initial air-to-water ratio expressed at 1 atm and 68°F) and u_w (superficial water velocity in pipe) or on y_o° and Q (water flow rate) can be represented within about ±3 percent by the equations:

$$(K_La)_{20} = 3.84 \ y_o^\circ \ Q^{2.85}$$

$$(K_La)_{20} = 3090 \ y_o^\circ \ u_w^{2.85} \tag{17}$$

where K_La is in hr^{-1}, Q is in gpm, and u_w is in ft/sec.

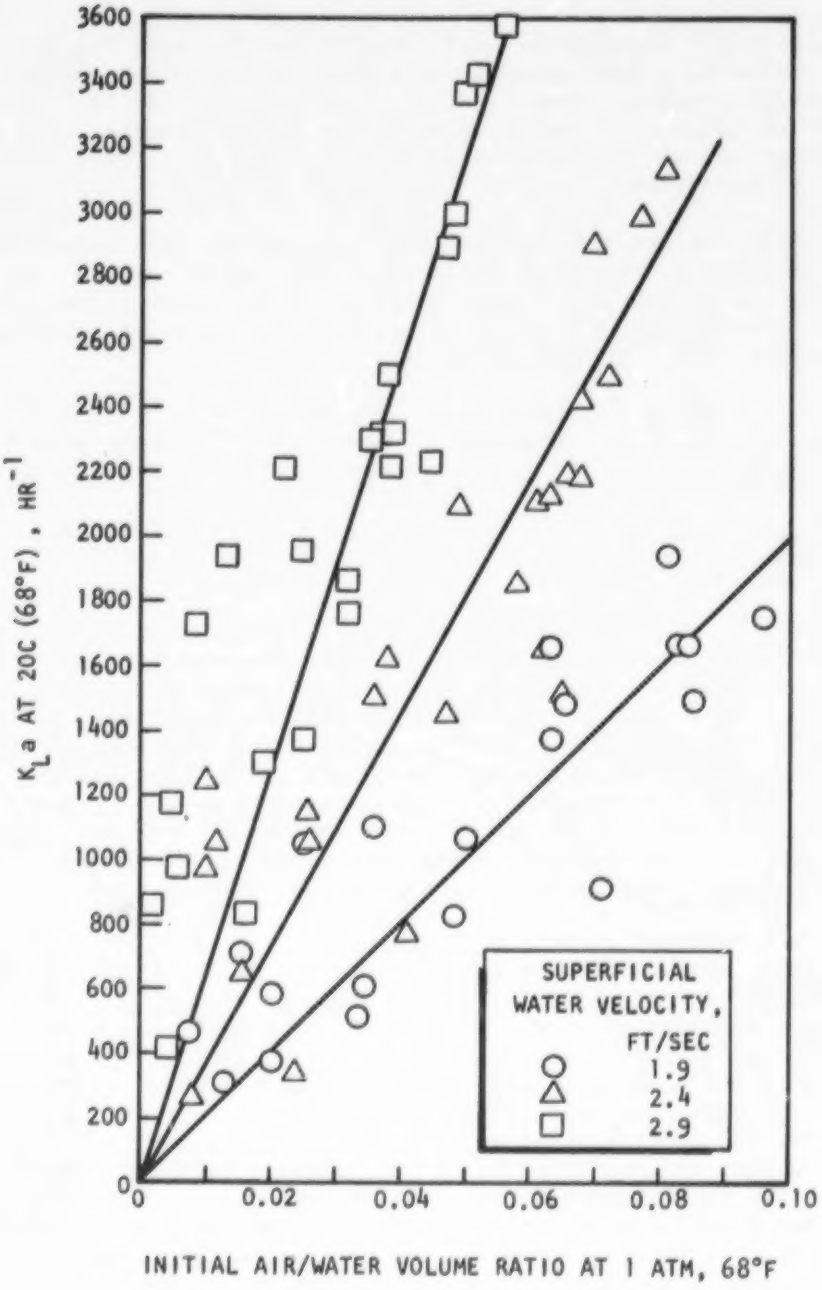

Figure 31. Experimental Mass Transfer Coefficients for Venturi Aspirator

Although Eq. 17 for venturi mass transfer coefficients was adequate for data reduction, a more general description was required for application to a design program. Specifically, an equation was desired which included the effects of throat velocity and throat diameter. The generalized equation was developed on an empirical basis, as described in the following paragraphs.

The work of Jackson and Collins (Ref. 17) was the only source of applicable experimental data which was found. This study compared the oxygen transfer and energy loss characteristics of two sizes of venturi aspirators. A comparison of the two units, with the range of variables investigated for each, is given below:

Venturi	Entrance Diameter (inch)	Throat Diameter (inch)	Throat Velocities (ft/sec)	Air-to-Water Volume Ratios
Large	3.75	1.25	23, 31, 36, 45	0.163-0.184
Small	0.75	0.25	21, 30, 37, 45	0.141-0.188

Conveniently, the contraction ratios for Jackson's units and aspirator used in the 2-inch U-tube in this project were essentially the same, 9 and 8 respectively. Unfortunately, Jackson's aspirators were horizontally mounted. The assumption that mass transfer is independent of orientation had to be made. Jackson's minimum throat velocities were comparable to the experimental throat velocity at 30 gpm (23.1 fps) for this investigation. Jackson operated only at approximately $y = 0.18$ with his lowest throat velocities. At 30 gpm the maximum air-to-water ratio attained was 0.057 for this investigation. Extrapolations had to be made to find a common basis of comparison with respect to air-to-water ratio.

A linear extrapolation of the 30 gpm curve (Fig. 31) to $y = 0.18$ gave K_La equal to 11,400 hr^{-1}. This value is plotted with Jackson's mass transfer coefficients as a function of throat diameter in Fig. 32. Evaluation of the slope shows that, at $y = 0.18$, K_La is approximately proportional to throat diameter raised to the -1.35 power. A plot of K_La versus throat velocity (with y approximately equal to 0.18) is shown in Fig. 33. The slopes for Jackson's two horizontal aspirators are 1.40 and 1.30; the slope for the vertical venturi tested in this project is 2.72. It should be noted that Jackson's lowest throat velocity is roughly equal to the largest for this investigation. The discrepancy in the slopes (i.e., a different throat velocity functionality) is probably due to the different orientation of the aspirators or the difference in throat velocity range. Since Jackson's data are for horizontal aspirators (the most likely orientation for large-scale facilities), these data were used as a basis for determining the throat velocity dependence. Therefore, K_La was concluded to be proportional to the 1.35 (mean of 1.30 and 1.40) power of throat

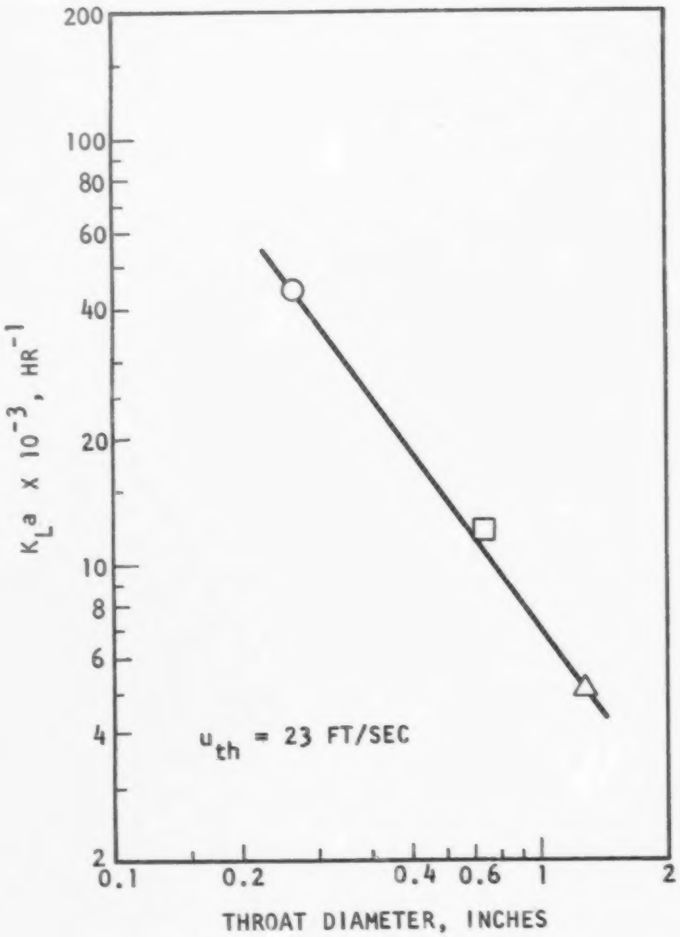

Figure 32. Effect of Venturi Throat Diameter on Mass Transfer Coefficient

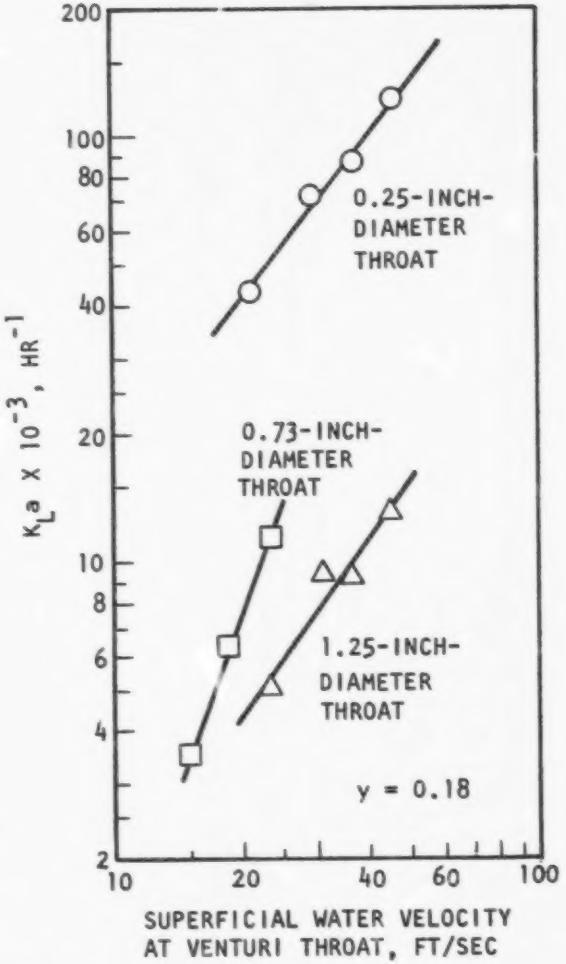

Figure 33. Effect of Venturi Throat Water Velocity on Mass Transfer Coefficient

velocity. Based on the linear air-to-water dependence shown in Fig. 31, the general form for the venturi mass transfer coefficient is:

$$K_La = 576\ y^\circ_o \left(\frac{u_4}{D_4}\right)^{1.35} \tag{18}$$

where K_La is the mass transfer coefficient at 68°F in hr^{-1}, u_4 is the throat velocity in ft/sec, D_4 is the throat diameter in inches, and y°_o is the initial air-to-water volume fraction at 1 atm and 68°F.

Equations 15 and 18 can be combined, with some rearrangement, to give

$$\frac{C_5 - C_3}{C_s - C_3} = 1 - \exp\left[\frac{-29.4\ y^\circ_o\ u_3^{0.35}\ E^{2.025}\ V}{D_3^{3.35}}\right] \tag*{(19)*}$$

in which the venturi entrance velocity, u_3, is in ft/sec; the venturi diffuser volume, V, is in ft^3; and the venturi entrance pipe diameter, D_3, is expressed in inches. For the more specific case of a venturi with a conical diffuser (of half-angle b), Eq. 19 becomes:

$$\frac{C_5 - C_3}{C_s - C_3} = 1 - \exp\left[\frac{-0.00222\ y^\circ_o}{\mathrm{Tan}(b)} \left(\frac{u_3}{D_3}\right)^{0.35} E^{2.025}(1-E^{-1/2})\ (1+E^{-1/2}+E^{-1})\right] \tag*{(20)*}$$

Equation 20 predicts that the amount of oxygen transfer in a venturi aspirator will increase as y°_o, u_3, or E increase, and will decrease as b or D_3 increase. The values of b and E have a strong effect on the oxygen transfer (primarily as they affect residence time in the diffuser). The air-to-water fraction also has a strong effect on the transfer, as should be expected. Neither the entrance velocity nor the entrance pipe diameter is predicted to have a very pronounced effect on the oxygen transfer. Representative parametric values for oxygen transfer in a venturi aspirator (with b = 7.5 degrees), as predicted by Eq. 20, are given on the top of the following page.

Potential users of Eq. 20 should keep in mind that it was developed from a limited set of data (the experimental data obtained during this project plus all applicable data which could be found in the literature). These data were for three venturi aspirators, with entrance pipe nominal diameters

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*Alternate convention used for expressing exponents, i.e., $\exp(a) = e^a$

y_o^o	u_3 (ft/sec)	D_3 (inch)	E	$\frac{C_5 - C_3}{C_s - C_3}$
0.05	2	2	4	0.0122
0.05	4	12	4	0.0083
0.10	2	2	4	0.0242
0.10	2	12	4	0.0130
0.10	2	24	4	0.0102
0.10	4	2	4	0.0307
0.10	4	12	2	0.0030
0.10	4	12	4	0.0165
0.10	4	12	6	0.040
0.10	4	12	8	0.071
0.10	4	12	10	0.111
0.10	4	12	12	0.158
0.10	4	24	4	0.0130
0.10	6	2	4	0.0353
0.10	6	12	4	0.0190
0.10	6	24	4	0.0150
0.10	8	2	4	0.0390
0.10	8	24	4	0.0165
0.15	2	2	4	0.0360
0.15	4	12	4	0.0247
0.20	2	2	4	0.048
0.20	4	12	4	0.033
0.25	2	2	4	0.059
0.25	4	12	4	0.041

of 3/4, 2, and 4 inches. The diffusers were conical in each case, with full-cone angles of about 7 degrees. The nozzle contraction area ratios were 8 and 9. Equation 20 was developed to permit design predictions, since no other design basis was available, and it should give reasonable estimates of venturi aspirator oxygen transfer for aspirators which are geometrically similar to the three for which experimental data exist. Equation 20 should also give reasonable predictions for substantially larger aspirators than these three, since the effect of diameter appears to be modest, as long as the aspirators have similar configurations.

However, for large scale applications the length and cost of a conical diffuser with a small divergence angle would become excessive, and other diffuser designs would probably be used: perhaps a cone with larger divergence angle, or with a contoured divergence section (e.g., the aspirators designed for the Jefferson Parish applications, as described in the next major section). Alternately, in large scale applications, the aspirator might be a "trough," i.e., have venturi contours in only one plane, with a rectangular flow cross section at any station. It would be fortuitous if Eq. 20 gave accurate predictions for such geometrically different types of venturi aspirators, or for a wide range of contraction area ratios differing from the 8 to 9 range represented by the experimental data. Additional data are needed to permit development of a more general relationship for predicting venturi oxygen transfer.

DATA REDUCTION PROGRAM

Mass transfer coefficients were calculated from the various sets of data generated during these projects, in order to reduce the oxygen transfer data to a common basis which could be used for design. It was necessary to develop a computer program to perform these calculations. The original version of the program was used to calculate coefficients for the pilot-scale data. Subsequently, the program was modified and used to calculate coefficients for the full-scale data obtained in Jefferson Parish and Port Arthur. The computation scheme, assumptions, and relationships which were used in the program are described in this section.

The major components of the computation scheme built into the computer program are shown in the flowsheet of Fig. 34. It can be seen that the program estimates an initial value for the mass transfer coefficient, K_L, performs finite-difference calculations throughout the experimental U-tube system, compares the calculated exit D.O. concentration with the experimental concentration, and repeats the iteration until satisfactory agreement is reached.

Solubility data for oxygen in water in 1-atmosphere air pressure (0.21-atmosphere oxygen partial pressure) were taken from Ref. 22, and curve-fitted over the temperature range 50° to 85°F with the equation

$$C_s = 187.6\ T^{-0.714} - 0.16 \tag{21}$$

with C_s in mg/l and T in degrees F. The solubility data for nitrogen in water at 1-atmosphere nitrogen pressure were taken from Ref. 23, and curve-fitted over the temperature range 50° to 85°F with the equation

$$C_s' = 242.0\ T^{-0.6} + 0.07 \tag{22}$$

with the same units as for Eq. 21 (superscript prime refers to nitrogen, while symbols without a superscript refer to oxygen). These data were adjusted to other pressures as required using Henry's Law.

In experimental runs for which D.O. concentration was measured at the aspirator exit, these values were used by the program. Where these values

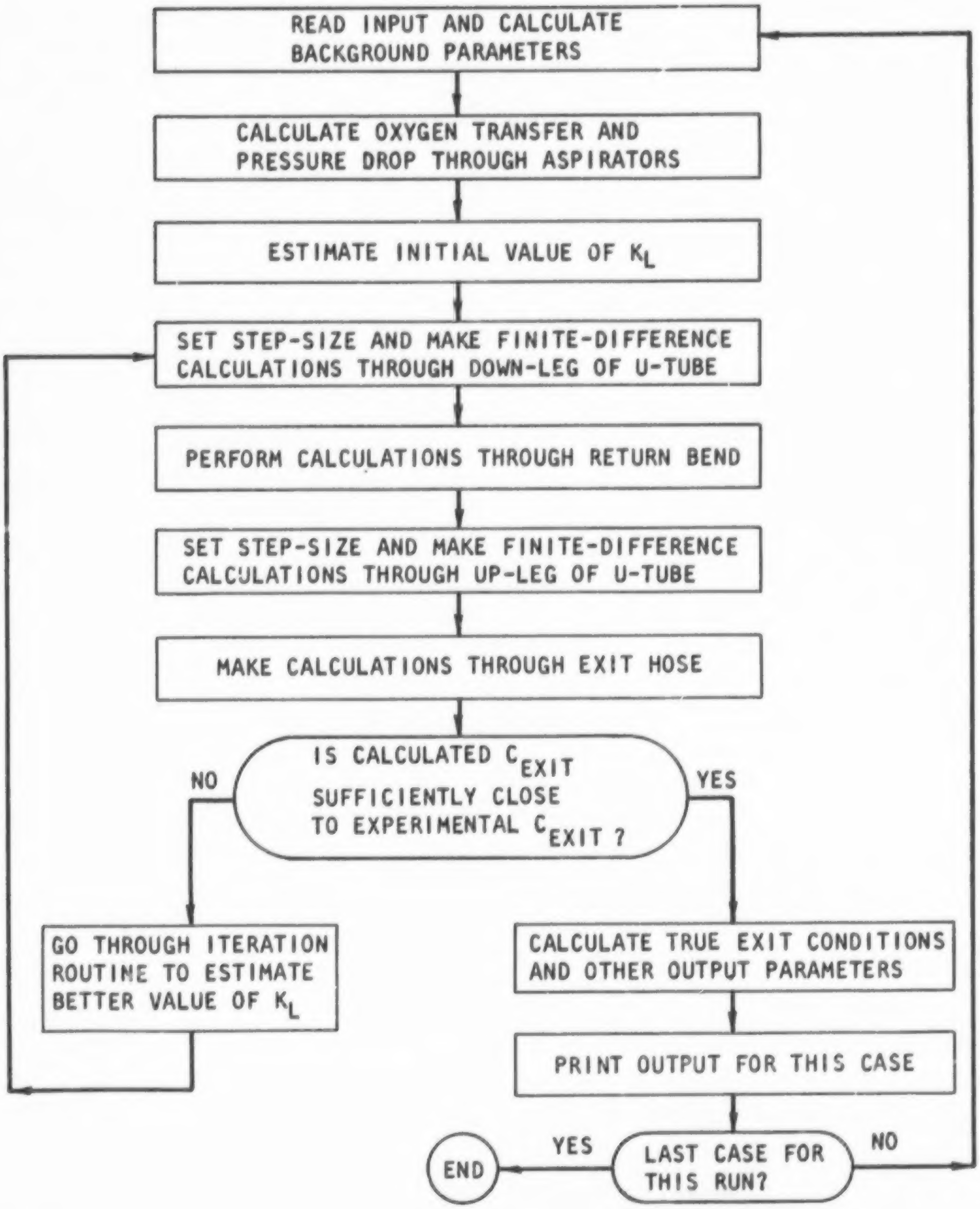
READ INPUT AND CALCULATE BACKGROUND PARAMETERS
CALCULATE OXYGEN TRANSFER AND PRESSURE DROP THROUGH ASPIRATORS
ESTIMATE INITIAL VALUE OF K_L
SET STEP-SIZE AND MAKE FINITE-DIFFERENCE CALCULATIONS THROUGH DOWN-LEG OF U-TUBE
PERFORM CALCULATIONS THROUGH RETURN BEND
SET STEP-SIZE AND MAKE FINITE-DIFFERENCE CALCULATIONS THROUGH UP-LEG OF U-TUBE
MAKE CALCULATIONS THROUGH EXIT HOSE
IS CALCULATED C_{EXIT} SUFFICIENTLY CLOSE TO EXPERIMENTAL C_{EXIT}?
NO
YES
GO THROUGH ITERATION ROUTINE TO ESTIMATE BETTER VALUE OF K_L
CALCULATE TRUE EXIT CONDITIONS AND OTHER OUTPUT PARAMETERS
PRINT OUTPUT FOR THIS CASE
LAST CASE FOR THIS RUN?
YES
NO
END

Figure 34. Computation Flowsheet for Data Reduction Program

were not obtained experimentally, they were estimated using Eq. 19. Nitrogen transfer in the aspirator was calculated with a relationship analogous to Eq. 19, with the assumption that K_La for nitrogen is 0.9 times the value for oxygen, based on Ref. 24 and 25.

The calculations for a single distance step in the U-tube employed the following equations (i.e., given values at the end of step n, these equations were used to calculate values at the end of step n + 1). All symbols are defined in the Glossary.

$$u_{m,n} = u_w(1 + y_n) \tag{23}$$

$$\Delta t_{a,n} = h/(u_{m,n} - u_s)$$

$$\Delta t_{w,n} = h/u_{m,n}$$

$$p_{t,n+1} = p_{t,n} - h\ F_n$$

$$C_{n+1} = C_n + K_La_n(C_s - C)_n\ \Delta t_{w,n}$$

$$C'_{n+1} = C'_n + K'_La_n(C'_s - C')_n\ \Delta t_{w,n}$$

$$n_{n+1} = n_n - K_La_n(C_s - C)_n\ \Delta t_{a,n}/M$$

$$n'_{n+1} = n'_n - K'_La_n(C'_s - C')_n\ \Delta t_{a,n}/M'$$

$$p_{n+1} = \frac{n_{n+1}(p_{t,n+1} - p_v)}{n_{n+1} + n'_{n+1} + n_{i,n+1}}$$

$$p'_{n+1} = \frac{n'_{n+1}\ (p_{t,n+1} - p_v)}{n_{n+1} + n'_{n+1} + n_{i,n+1}}$$

$$y_{n+1} = \frac{p_{t,n}\ y_n}{p_{t,n+1}} - \frac{a_n\ \Delta t_{w,n}\ [K_L(C_s - C)_n + K_L(C'_s - C')_n]}{\rho_{a,n+1}}$$

$$a_{n+1} = \frac{y_{n+1}\ X}{1 + y_{n+1}}$$

These equations apply for iteration steps in the down-leg, return bend, up-leg, or exit section--with appropriate values for F, u_s, and X in each section. The change in pressure per unit length in the down-leg (F_d) was based on empirical relationships derived from the experimental data (Eq. 9 was used in the final version of the program). The value of F in the return bend was estimated from conventional fluid dynamics relationships, considering the two-phase velocity. The Hershey correlation was used to estimate values of F at each step in the up-leg, as discussed in the previous section on Pressure Loss Correlations. The values of u_s and X, obtained from the motion pictures of two-phase flow in the experimental apparatus (as described in the Pilot-Scale Experimental Results section), were $u_{s,d} = 0.2$ ft/sec, $u_{s,u} = -0.2$ ft/sec, and $X_d = X_u = 470$ ft^{-1}.

The entering D.N. (dissolved nitrogen) concentration was assumed to be saturated with respect to normal air at the ambient pressure. The values of K_L were estimated at 0.9 times K_L in accounting for nitrogen transfer in the system.

MASS TRANSFER COEFFICIENTS

The mass transfer coefficients calculated from the experimental data with the data reduction computer program are presented in Appendices A and B for the pilot-scale and full-scale data, respectively. Results from the analysis of the pilot-scale data were used in design of the full-scale field installations. This first analysis was presented in Ref. 4 and is summarized here. Values of the mass transfer coefficient for the pilot-scale data are presented in Fig. 35 through 39, plotted as a function of initial air-to-water volume ratio. At the time of this analysis, three specific conclusions were drawn from these results: (1) K_L is essentially independent of water velocity over the range 1.4 to 3.4 ft/sec (with respect to the results of that investigation); (2) K_L decreases slightly with increasing air-to-water ratio, except that the negative slope becomes quite large for air-to-water ratios less than about 0.04; (3) K_L decreases slightly with increasing U-tube depth. Limitations of experimental accuracy at small air-to-water ratios (y_0 less than about 0.03) raised some question about the validity of the results for very small values of y_0. At low ratios, the air orifice manometer differential was very small, leading to possibly large air flow rate errors. Also, for low y_0, the change in D.O. across the U-tube was small, leading to comparatively larger errors in the difference.

These pilot-scale mass transfer coefficient data were curve-fitted to form a generalized predictive equation for use in design. After considering the limitations on experimental accuracy and the fact that field installations normally would be designed for y_0 levels in the range of 0.05 to 0.2, it was decided at that time to curve-fit only the data for y_0 above 0.04. A single-parameter, least-squares analysis was first performed on each set of data for a single U-tube depth, considering six

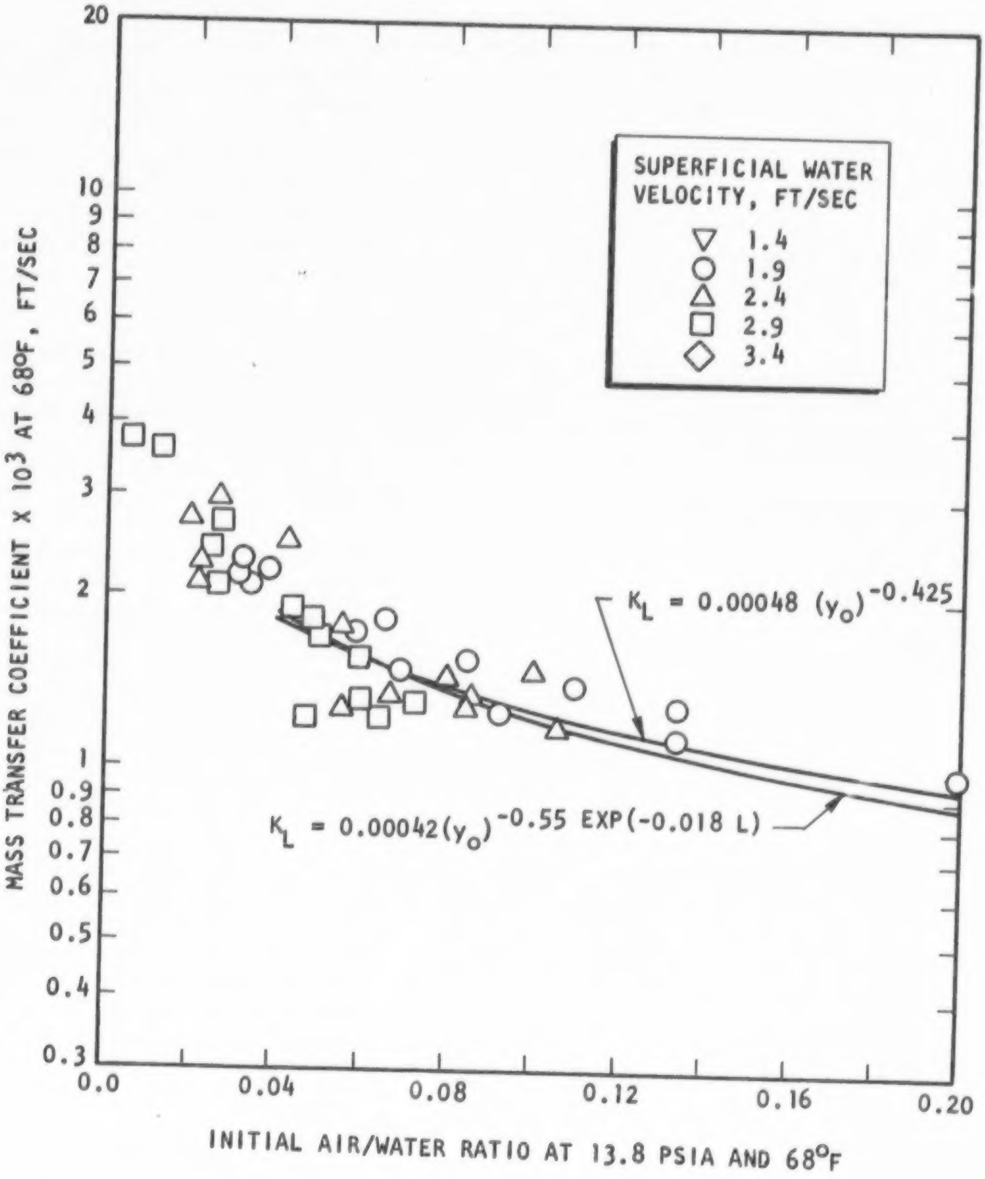

Figure 35. Experimental Mass Transfer Coefficients for 9-Ft U-Tube (2-inch pipe)

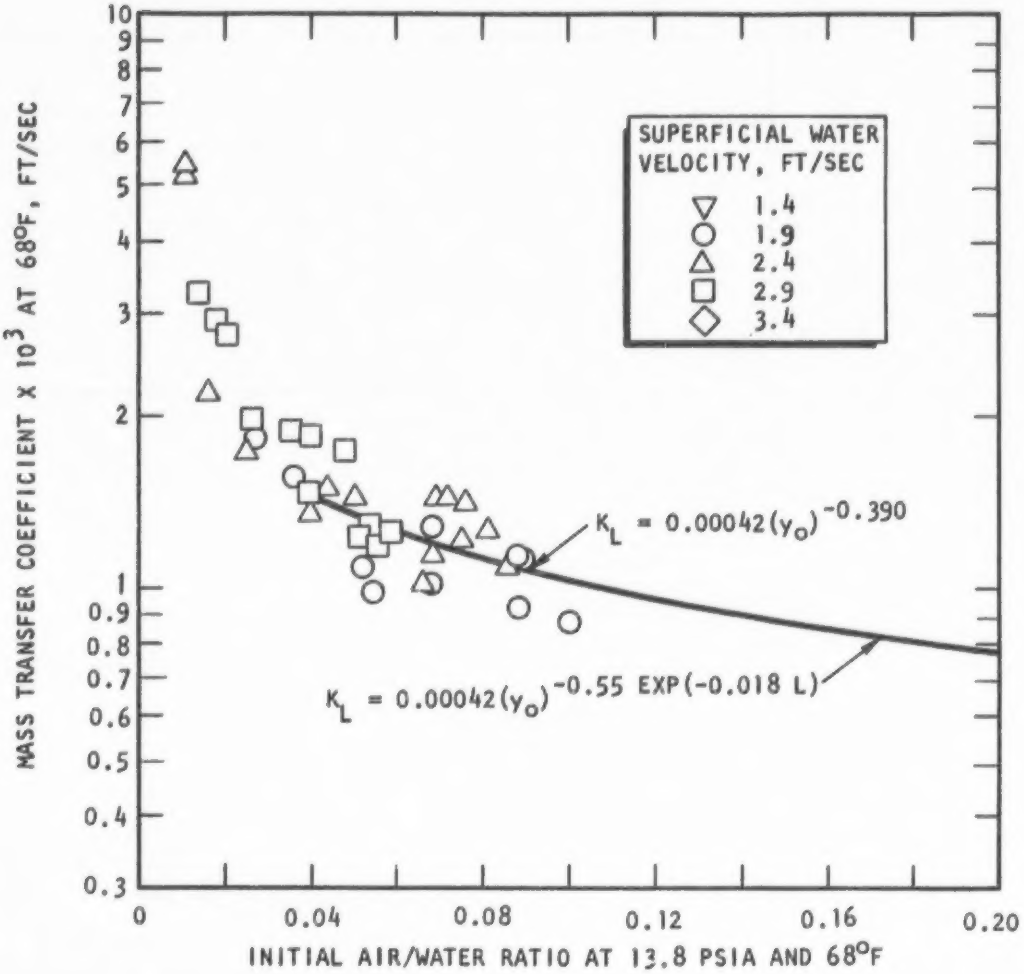

Figure 36. Experimental Mass Transfer Coefficients for 19-Ft U-Tube (2-inch pipe)

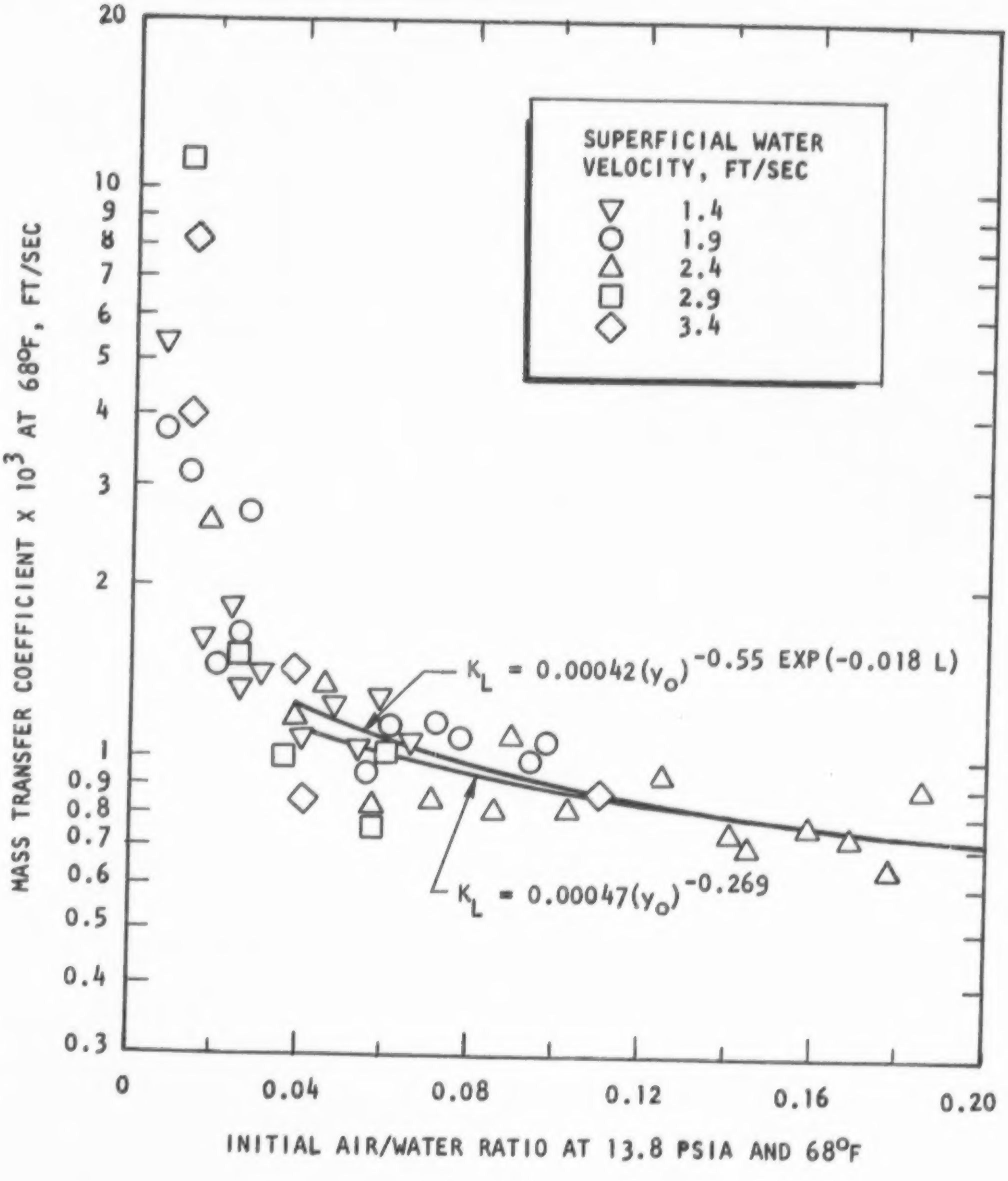

Figure 37. Experimental Mass Transfer Coefficient for 28-Ft U-Tube (2-inch pipe)

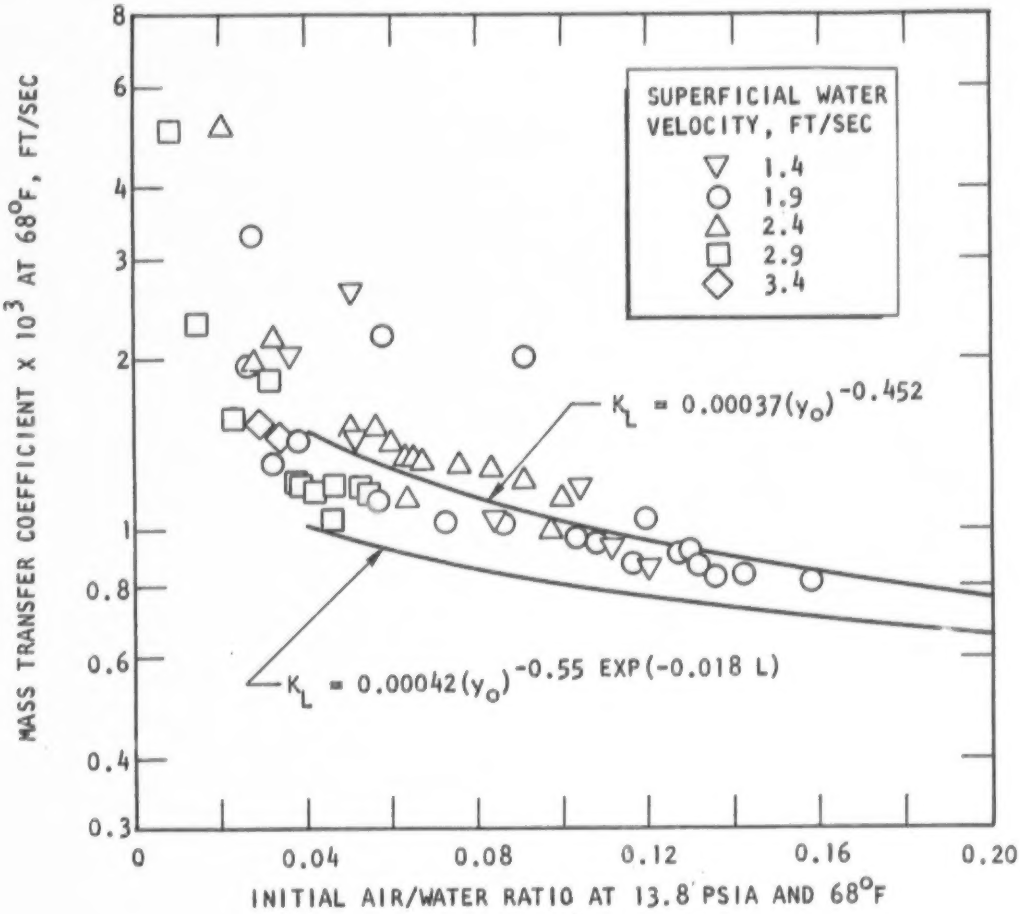

Figure 38. Experimental Mass Transfer Coefficients for 37-Ft U-Tube (2-inch pipe)

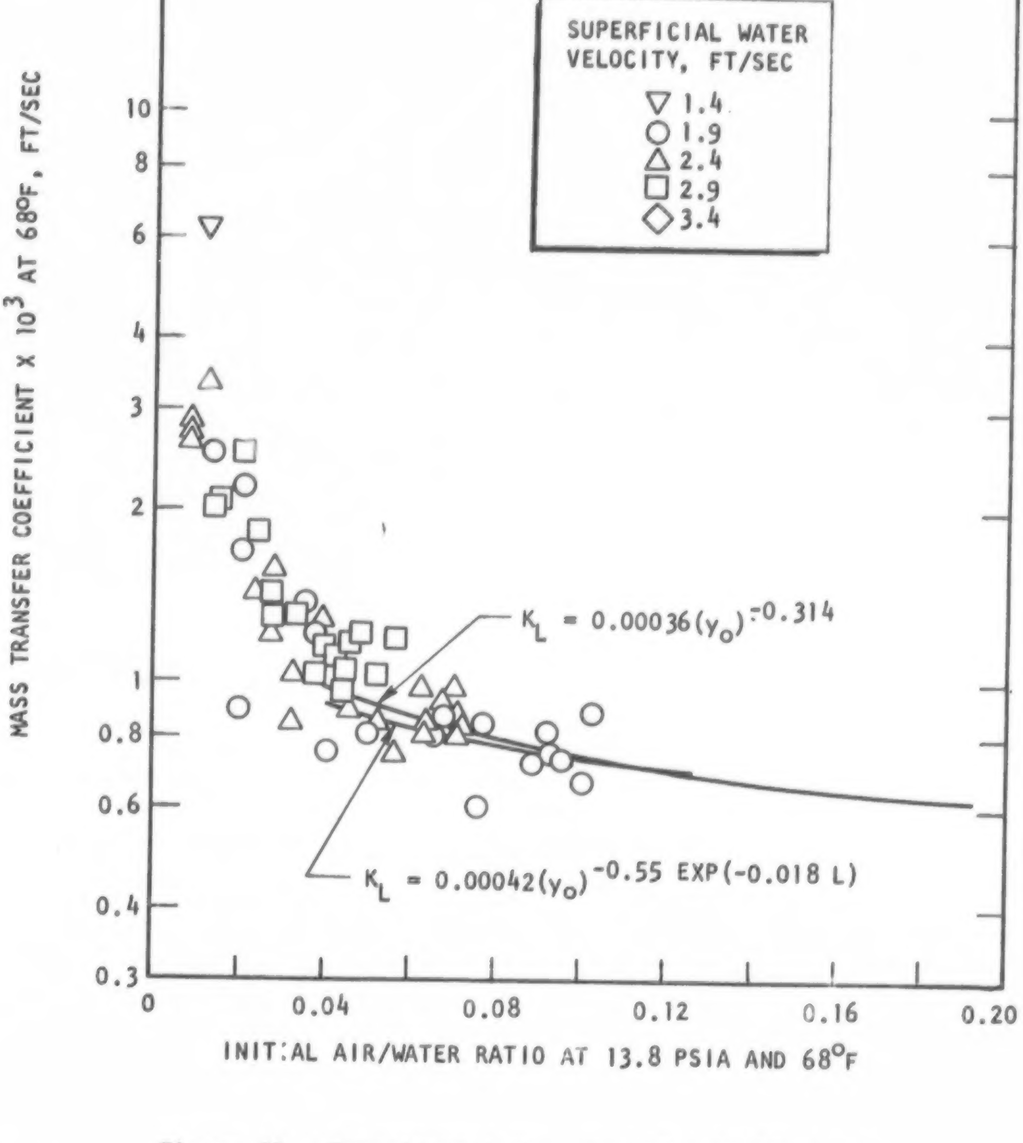

Figure 39. Experimental Mass Transfer Coefficients for 45-Ft U-Tube (2-inch pipe)

different forms of a single-parameter equation. The best single-equation form for all five sets of pilot-scale data was

$$K_L = A_1 (y_o)^{B_1}$$

where A_1 and B_1 are constants. The best-fit equation in each case is plotted and written on the appropriate graph (Fig. 35 through 39).

The five individual equations of this form were then modified to yield a general expression for K_L as a function of y_o and U-tube depth. The average value of A_1 for the five depths (0.00042) was assumed constant. A new exponent (B_2) was defined so that the value of K_L at $y_o = 0.10$ was the same for each depth as the value of K_L predicted with the least squares equation derived for that specific depth, i.e.,

$$K_L = 0.00042 \ (0.10)^{B_2}$$

The resulting values for B_2 as a function of depth are as follows:

Depth, feet	B_2
9	-0.487
19	-0.391
28	-0.316
37	-0.398
45	-0.250

It is apparent that B_2 becomes more positive with depth except for the 37-ft U-tube. A semilogarithmic representation of B_2 versus depth gave an excellent linear relationship except for the 37-foot depth. The conclusion was that B_2 could be represented as $B_2 = A_2\exp(A_3L)$, where L is depth in feet. The constants A_2 and A_3 were evaluated as -0.55 and -0.018, respectively, giving the final form of the equation (for y_o greater than 0.04) as

$$K_L = 0.00042 \ (y_o)^{-0.55 \exp(-0.018 L)} \tag{24}$$

where K_L is the mass transfer coefficient at 68°F, in ft/sec, y_o is the air-to-water ratio at 13.8 psia and 68°F, and L is the U-tube depth in feet. This equation is also plotted in Fig. 35 through 39. It can be seen that for all depths except 37 feet, Eq. 24 predicts results almost identical to those from the individual equations for each depth. The agreement with the least-squares equation at other depths strongly suggests that the 37-foot data have some bias.

Analysis of the data from the full-scale installations proceeded along slightly different lines. Whereas the pilot-scale data were correlated in terms of initial air-to-water volume ratio and U-tube depth, it was decided subsequently that it would be preferable not to have the U-tube depth as one of the primary independent variables. Rather, it was decided to correlate the mass transfer coefficients from the full-scale data as a function of an "average" air-to-water volume ratio ($\bar{y}$) in the U-tube rather than an initial one at specified standard conditions (y_o). It was then expected that most of the dependence on length would be removed. The data obtained at both Port Arthur and Jefferson Parish, Stations 5 and 7 (tabulated in Appendix B), are presented in Fig. 40. Here, y is defined as a residence time weighted average y:

$$\bar{y} = \left(\int \frac{y\,dl}{u} \Big/ \int \frac{dl}{u}\right) \qquad (25)$$

where u is the local superficial water velocity, dl is a differential path length in the U-tube, and y is the local air-to-water-volume ratio. In practice, an approximate form of Eq. 25, which could be evaluated for an as-yet-unsolved design case, was used to calculate values of $\bar{y}$.

It can be seen that there is much more scatter in the field data than for the pilot-scale results. This is not unexpected in view of the many uncontrollable variations in a sewer line, and the fact that these data were taken in two different states and over a period of several days at each field site. It is also interesting to note that there are no significant differences between the data from Jefferson Parish and those from Port Arthur.

To determine a correlation representing the data presented in Fig. 40, several other independent variables were defined. These are $\bar{p}$, the residence time weighted average pressure; $\bar{u}$, the residence time weighted average superficial water velocity; and C_o, a variable equal to the D.O. concentration minus the immediate oxygen demand of the incoming stream. It is recognized that there are probably many more significant independent variables than the ones just listed; however, these were judged to be the most important ones for use in developing a correlation to be used for design purposes.

Many models involving various combinations of these independent variables were tested using a multiple stepwise linear regression program. It was determined that the most significant variable other than $\bar{y}$ was the average velocity, $\bar{u}$. The other two variables, $\bar{p}$, and C_o, as well as various combinations of these, did not explain the variability of the data in Fig. 40 as well as $\bar{u}$.

Upon examination, the dependence of K_L upon velocity appears to contradict one of the conclusions that was drawn from the pilot-scale data. However, further study indicates that the velocity effects noted in the

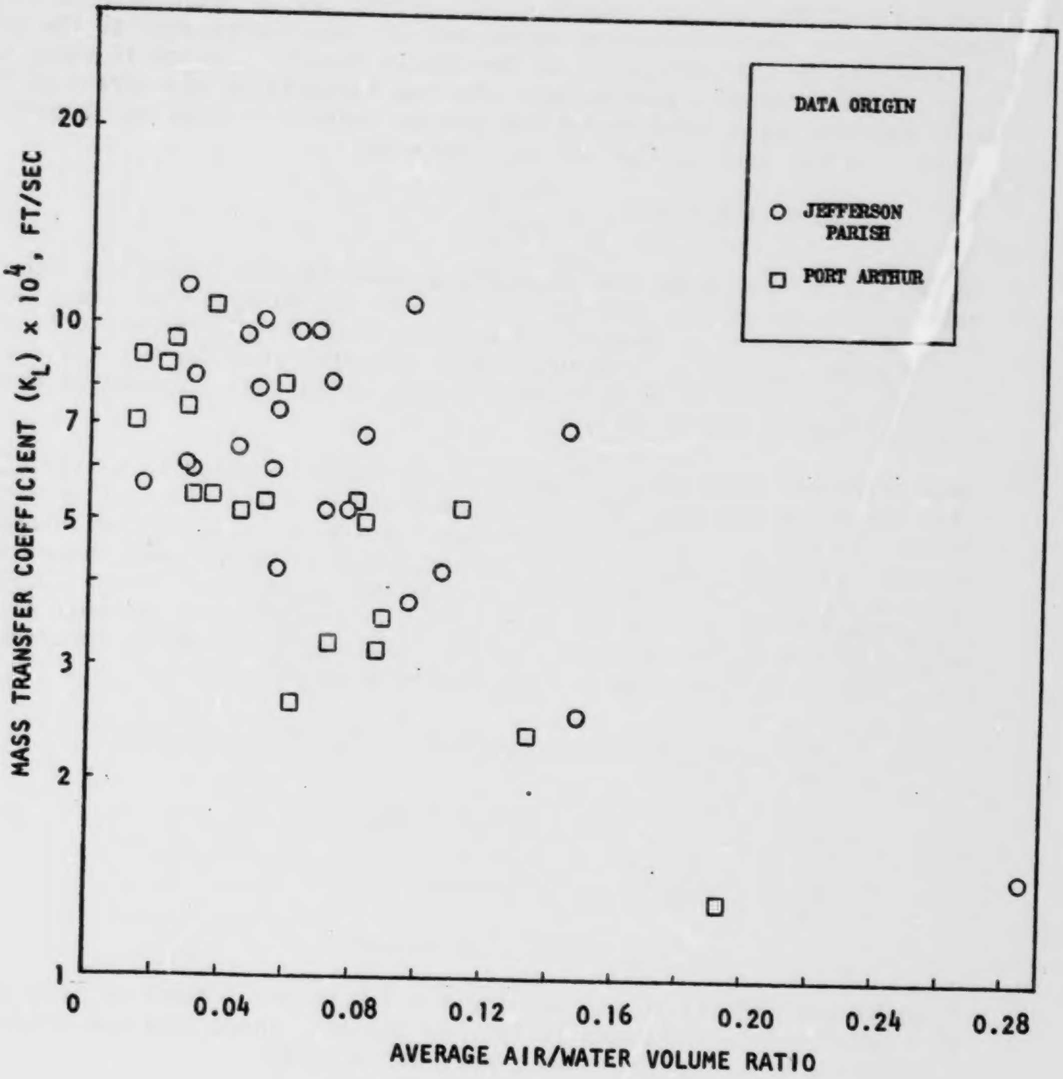

Figure 40. Experimental Mass Transfer Coefficients for Field Installations

two sets of data are not inconsistent. First, it is reasonable to expect that if there were a velocity dependence it would be related to the effect of velocity on the turbulence of the inflow stream. Figure 41 shows the experimental transfer coefficient after an estimate of the effect of $\bar{y}$ has been removed, as a function of the average velocity. This was constructed by fitting the data in Fig. 40 with the model

$$\ell n\ K_L = b_o \bar{y} + b_1 \qquad (26)$$

where b_o and b_1 were determined using a least-squares criterion. The ordinate of Fig. 41 is just ($\ell n\ K_L - b_o\ \bar{y}$). It can be seen that these residuals tend to increase as a function of $\bar{u}$ up to about $\bar{u} = 2.2$ ft/sec. After that, they remain relatively constant. This indicates that for $\bar{u} \geq 2.2$ ft/sec, the flow is sufficiently turbulent so that no further increase in mass transfer coefficient occurs.

This threshold phenomenon is probably why there appeared to be little velocity effect in the data from the pilot-scale U-tube. The vast majority of those data had velocities greater than 2.4 ft/sec. Taking the threshold velocity as approximately 2.2 ft/sec appeared to be the best choice for correlating the data from the full-scale installations. It was found that the general form, $K_L = b_o \exp(b_1\bar{y})$, was the simplest and yet most efficient model for fitting the data in Fig. 40. Letting b_o and b_1 be functions of $\bar{u}$ up to $\bar{u} = 2.2$ ft/sec led to the following correlation

$$K_L = 6.16\text{x}10^{-4} \exp\ [0.0963\ \bar{u} + (-10.2908+4.3516\bar{u})\bar{y}] \qquad (26a)$$

$$\text{for } \bar{u} \leq 2.2 \text{ ft/sec}$$

$$K_L = 7.62\text{x}10^{-4} \exp\ [-0.7173\bar{y}] \qquad (26b)$$

$$\text{for } \bar{u} > 2.2 \text{ ft/sec}$$

Equation 26a reduces to Eq. 26b for $\bar{u} = 2.2$ ft/sec. Plots of this regression and the data are given in Fig. 42 and 43. These data and regression curves were separated into two graphs for clarity.

Comparing the field data for large-scale U-tube systems in aerating untreated sewage with the earlier data from the pilot scale U-tube system aerating tap water, it was found that K_L values for the field data were almost always lower than the corresponding values derived from the tests with tap water, as expected. There was a somewhat larger dependence of K_l on y_o for the pilot-scale data. Comparing the two sets of data at conditions in the range of most practical interest, i.e., approximately 30- to 40- foot U-tube depths and y_o in the range of 0.05 to 0.2, gave

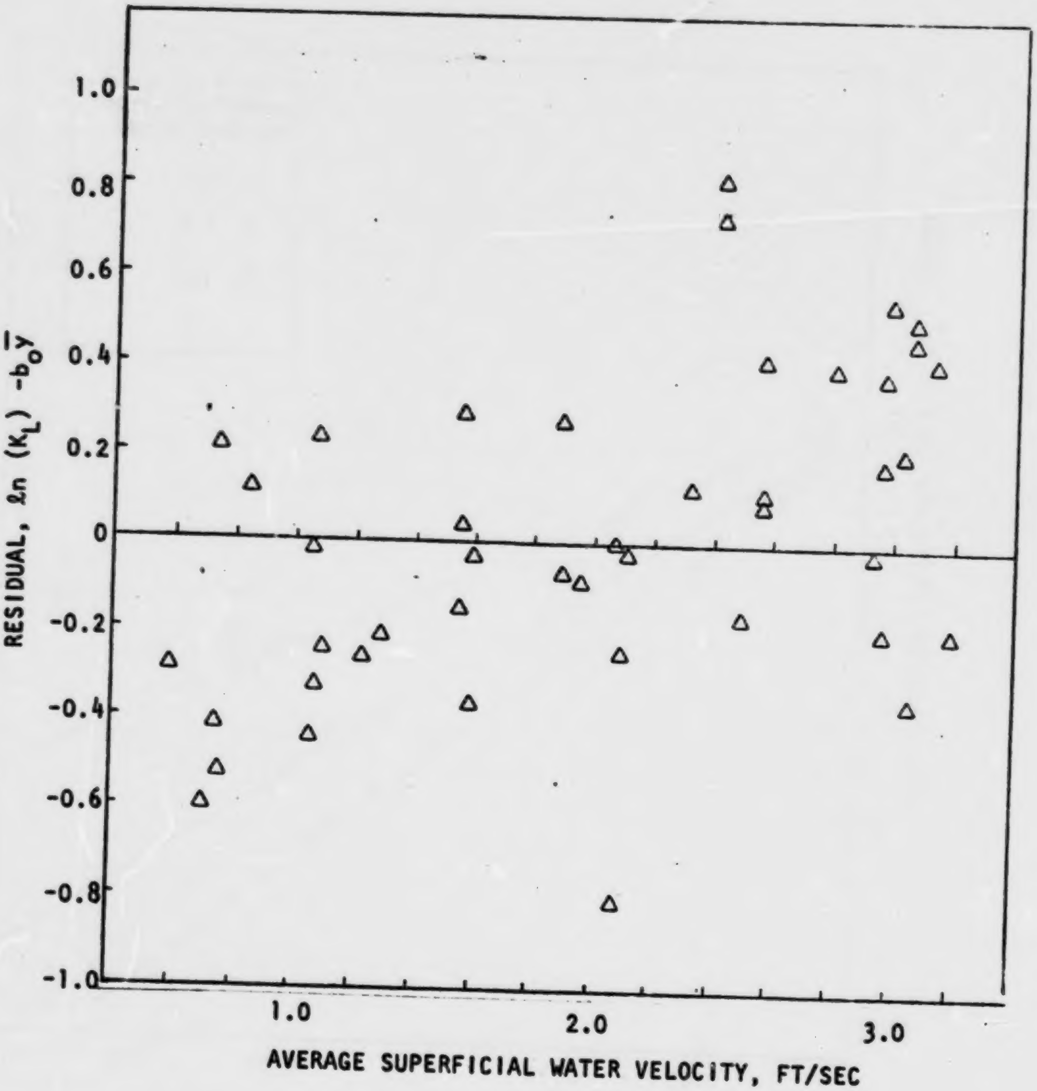

Figure 41. Experimental Mass Transfer Coefficient Residual After Main Effect of Average Air/Water Volume Fraction is Removed

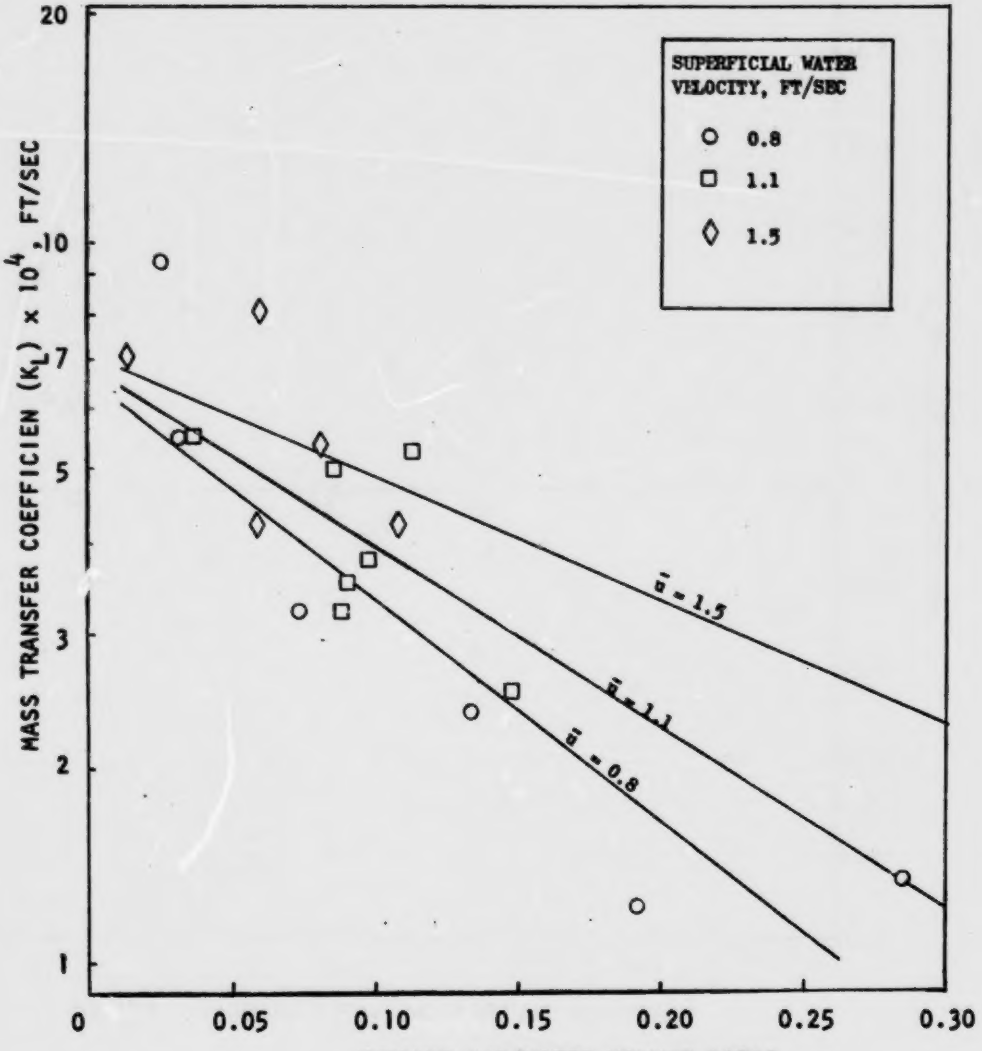

Figure 42. Experimental Mass Transfer Coefficients for Field Installations for Average Water Velocity Less Than 1.8 ft/sec

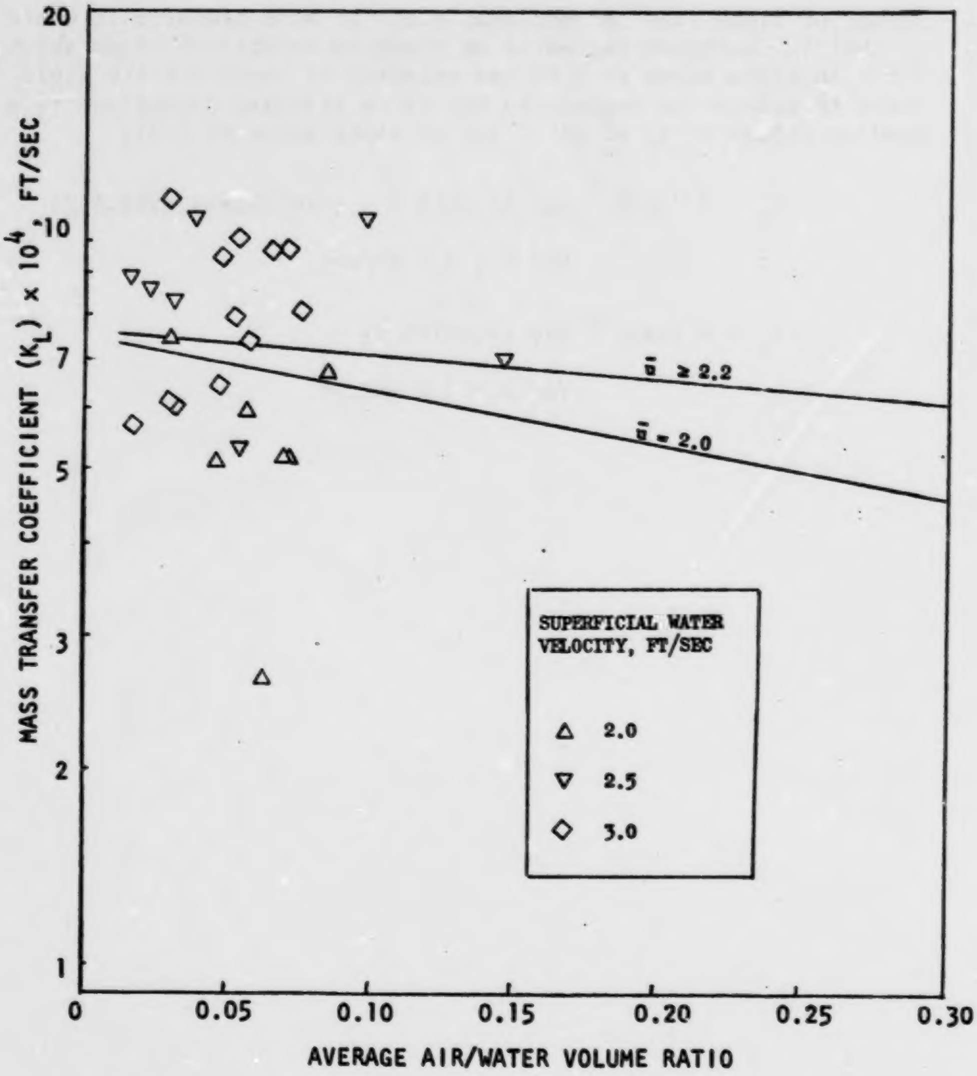

Figure 43. Experimental Mass Transfer Coefficients for Field Installations for Average Superficial Water Velocity Greater Than 1.8 ft/sec

values of alpha (the conventional ratio of mass transfer in waste water to that in deaerated tap water at standard conditions) from about 0.7 to 0.9. An alpha value of 0.80 was selected to represent the field data, in order to reduce the regression Eq. 26 to standard conditions (i.e., to predict values of K_L at 20° C for an alpha value of 1.0):

$$K_L = 7.70\text{x}10^{-4} \exp\left[0.0963\,\bar{u} + (-10.2908+4.3516\,\bar{u})\bar{y}\right] \qquad (27a)$$

$$\text{for } \bar{u} \leq 2.2 \text{ ft/sec}$$

$$K_L = 9.52\text{x}10^{-4} \exp\left[-0.7173\,\bar{y}\right] \qquad (27b)$$

$$\text{for } \bar{u} > 2.2 \text{ ft/sec}$$

SECTION VIII

U-TUBE DESIGN

The basic goal in any U-tube design effort is to provide a system which will effectively absorb as much oxygen as possible within the specfic requirements and constraints of the application. In some cases, the goal will be roughly to dissolve as much oxygen as possible, within some constraint on head loss or costs. In other cases, the goal will be more nearly to dissolve some required amount of oxygen with minimum head loss. There are endless variations and particular constraints which may be encountered. The purpose of this section is to summarize design bases and techniques which, together with good engineering judgment, can be used to design a U-tube aeration system. Examples are given in the final subsection of preliminary design and economic comparisons between U-tube systems and some other aeration systems.

DESIGN VARIABLES AND GENERAL CONSIDERATIONS

A U-tube aeration system consists of two basic elements: (1) a device for introducing or entraining air into a flowing water stream, followed by (2) a vertical U-shaped flow path to provide residence time in a zone of above-atmospheric pressure during which oxygen absorption from the entrained air takes place under favorable driving force conditions. (For simplicity, reference will be made only to use of air, although the phrase "air or oxygen" could be substituted in almost all cases.) The air entrainment component ordinarily will be either some type of aspirator or some type of diffuser to introduce compressed air. The U-shaped flow path can take various forms, e.g., a pair of vertical pipes connected by a 180-degree return bend at the bottom, a pair of concentric pipes with flow downward through one passage and upward through the other, or a rectangular "trough" with a vertical partition to force water flow down one side of the partition, under the partition, and up the other side.

There are tradeoffs to consider in choosing the type of air entrainment element. A diffuser with compressed-air source will be more flexible (both in design conditions and in operation), will permit use of higher air-to-water ratios, and will generally have lower head losses than a corresponding aspirated-air system. On the other hand, use of an aspirator as the air entrainment element has the advantages of requiring no moving parts, essentially zero maintenance, and can make use of natural head in situations in which the elevation profile of the flowing stream provides this.

Major considerations in the conceptual design of the vertical U-shaped flow path include two competing requirements: (1) oxygen transfer is generally enhanced by having low velocities, hence long residence times, but (2) it is necessary to keep the velocities high enough (particularly in the upward path) to prevent sedimentation and plugging in the system.

It is also important to keep the velocity in the downward path high enough to avoid the slug flow regime. If the application is aeration of waste water in a sewer, particular care must be taken to avoid any chances for plugging. In such applications, it probably is best to use a pair of vertical pipes connected by a 180-degree return bend at the bottom, to provide a smooth flow path throughout the system. It is also important in this type of application to size the upward pipe to maintain velocities high enough to prevent settling of solids--generally in the range of 3 to 5 ft/sec minimum. If the application is aeration of a natural water stream or treated effluent, it should be possible in most cases to use either a pair of concentric pipes (for low to moderate capacities) or a rectangular trough with center partition (for large capacities). Either of the latter configurations is less expensive than the type of configuration recommended for a sewer application.

Other variables which can be controlled, although not always independently, include: pipe sizes (or, more generally, flow cross-sectional areas) in various portions of the system, velocities (which are determined by the flow areas), air-to-water ratio, U-tube depth, and some other aspects of the system geometry. There are generally many combinations of design configurations and parameters which will produce a given amount of oxygen transfer. It is the task of the designer to determine those conditions which best meet his requirements, including consideration of initial and operating costs.

U-TUBE DESIGN PROGRAM

A computer program was developed to perform parametric design computations for U-tube aeration systems. It is almost necessary to use a computer program in making accurate design calculations for such systems because of the need to make finite-difference calculations with reasonably small step-sizes. Although parametric design curves or regression equations representing them could easily be presented for particular cases, this would not be of much general use since the specific requirements for different applications can cause substantial changes in the parametric performance characteristics. The design problem becomes particularly difficult in cases where the exit pressure is specified but the entrance pressure is unknown; it then becomes necessary to iterate the series of finite-difference calculations in order to converge on a solution which also matches the specified exit pressure. Because of the complexity of the computations, the design bases and system design criteria which were developed during these projects were incorporated into a computer program.

Actually, two versions of the design program were developed as the two projects evolved. The initial design program, which was developed from the pilot-scale data, was used in design of the full-scale U-tube systems for Jefferson Parish and Port Arthur; this already has been discussed in the section on Full-Scale Evaluation Tests. Subsequently, the program was improved, making use of the full-scale field data, into the form described in this section.

Configurations and Problem Type Options

Three major configurations or problem types can be analyzed with the program: (1) aspirated-air U-tubes installed in a force main (i.e., full-flowing pipe under pump head), as illustrated by the schematic sketch in Fig. 44; (2) compressed-air U-tubes installed in a force main, as illustrated by the sketch of Fig. 45; and (3) eductors, which are standard, commercially available units (sometimes called air-lift pumps), in which compressed air is injected at the bottom of a vertical tube through which a liquid is flowing upward. Therefore, eductors are essentially compressed-air U-tubes with the diffuser located at the bottom of the up-leg (station 9 in Fig. 45). It would be straightforward to modify the program to analyze other variations in U-tube configurations. The symbols shown for various dimensions in Fig. 44 and 45 are those used by the program, some of which appear in the output.

Program Outline and Description

The major calculation steps of the design computer program are shown in the flow-sheet of Fig. 46. It can be seen that the program repeats most of the calculations interatively until the convergence criterion for the particular case is satisfied. The usual procedure was to iterate the entrance pressure (p_1) until the calculated exit pressure (p_{12}) matched the specified exit pressure within a given tolerance, for specified values of entrance and exit pipe elevations plus other variables. The convergence techniques had to be somewhat more complex than those used for the data reduction program.

The usual input variables are (for the aspirated-air U-tube option):

- Geometric information about the venturi aspirator
- Radii of curvature of bends and elbows
- Slip velocities and values of X to characterize bubbles
- Throat pressure (or venturi contraction area ratio)
- Ambient pressure
- Water temperature
- Alpha
- Inlet D.O. concentration
- Water flowrate
- Initial air-to-water ratio

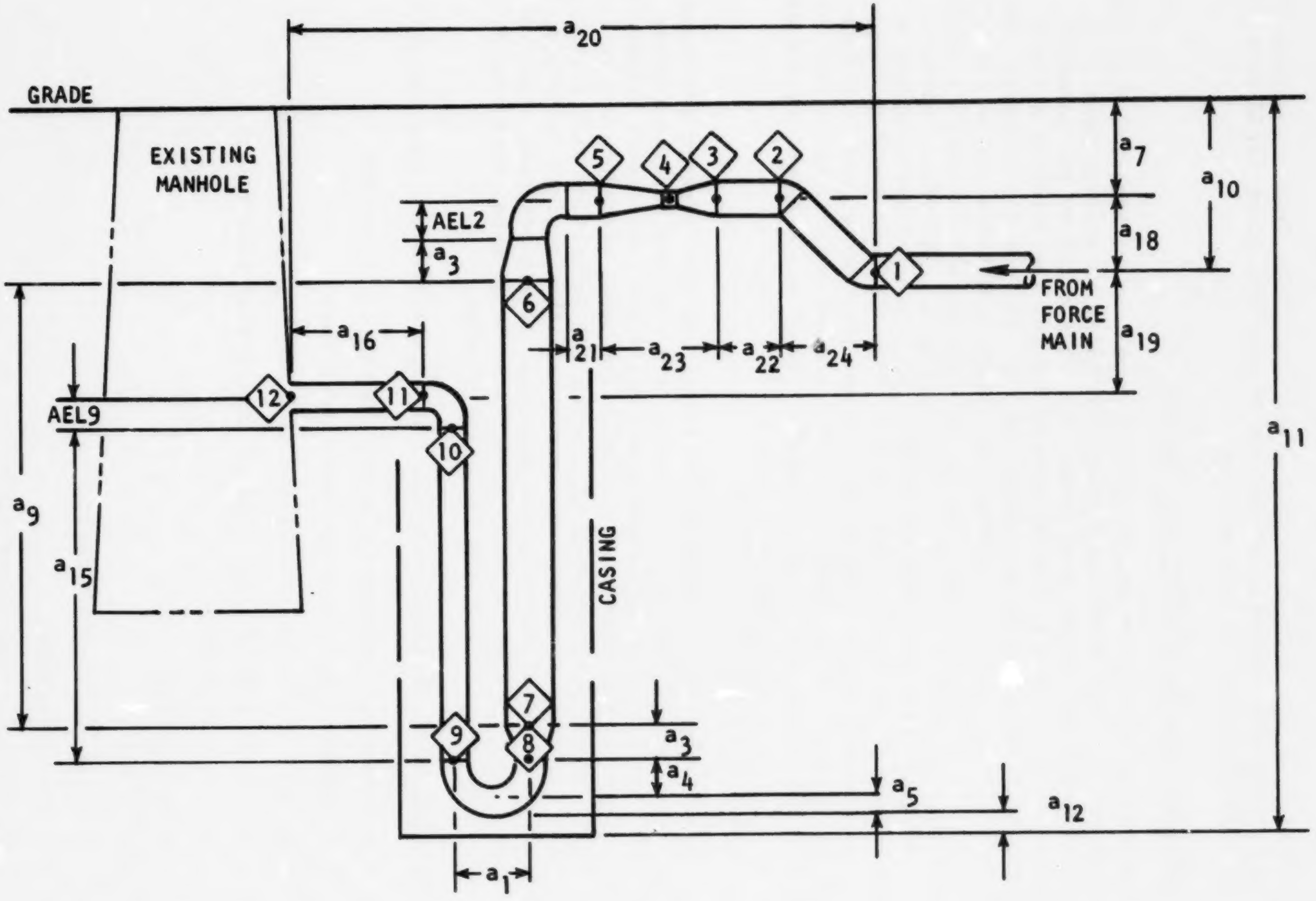
a_{20}
GRADE
EXISTING MANHOLE
AEL2
a_3
5
4
3
2
1
a_7
a_{10}
a_{18}
FROM FORCE MAIN
a_{19}
6
a_{16}
a_{21}
a_{23}
a_{22}
a_{24}
12
11
AEL9
10
a_{11}
a_9
a_{15}
CASING
7
9
8
a_3
a_4
a_5
a_{12}
a_1

Figure 44. Schematic Diagram of Aspirated-Air U-Tube

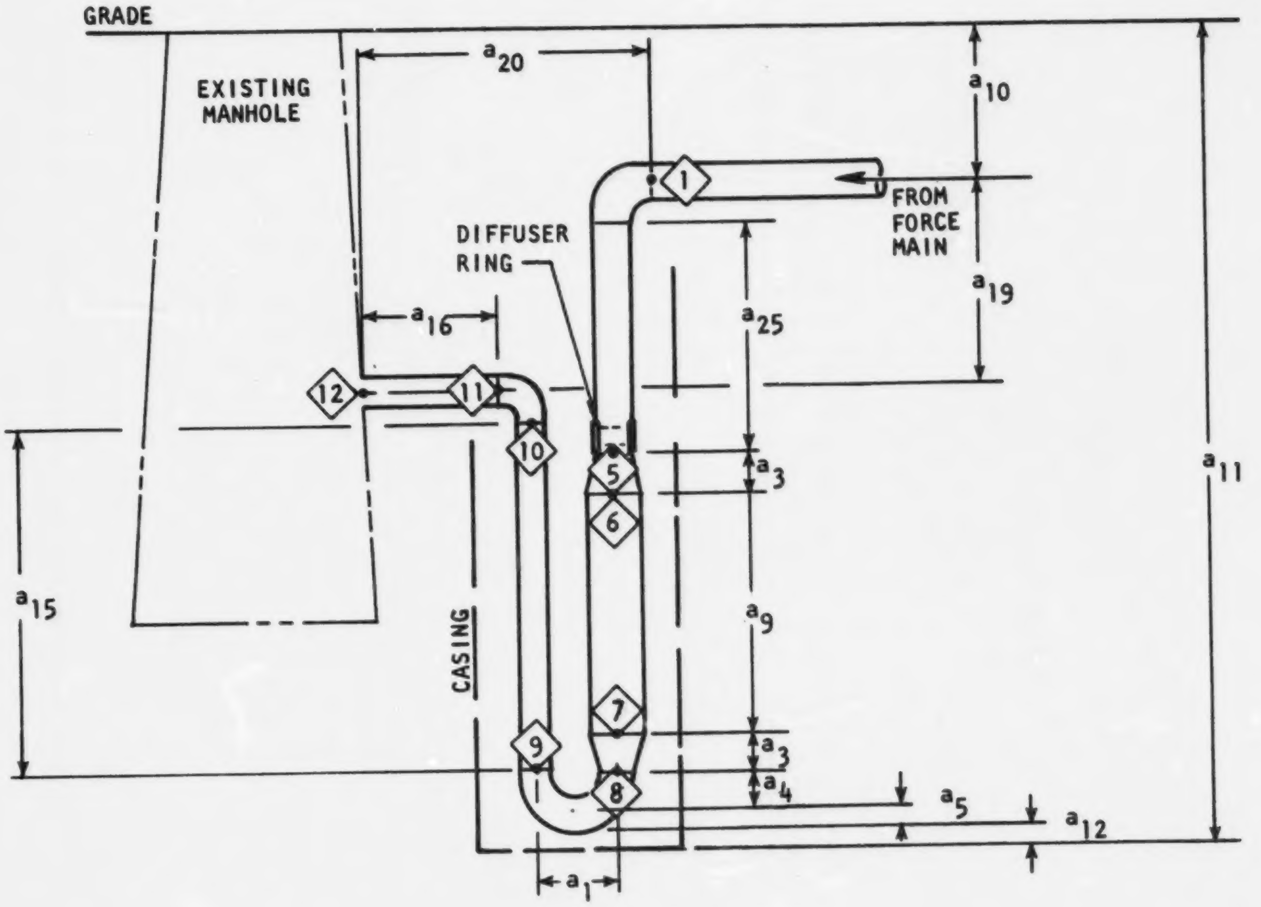
GRADE
EXISTING MANHOLE
a_{20}
a_{10}
a_{11}
1
FROM FORCE MAIN
DIFFUSER RING
a_{19}
a_{25}
a_{16}
12
11
10
5
6
a_3
a_{15}
a_9
CASING
7
9
a_3
a_4
8
a_5
a_{12}
a_1

Figure 45. Schematic Diagram of Compressed-Air U-Tube

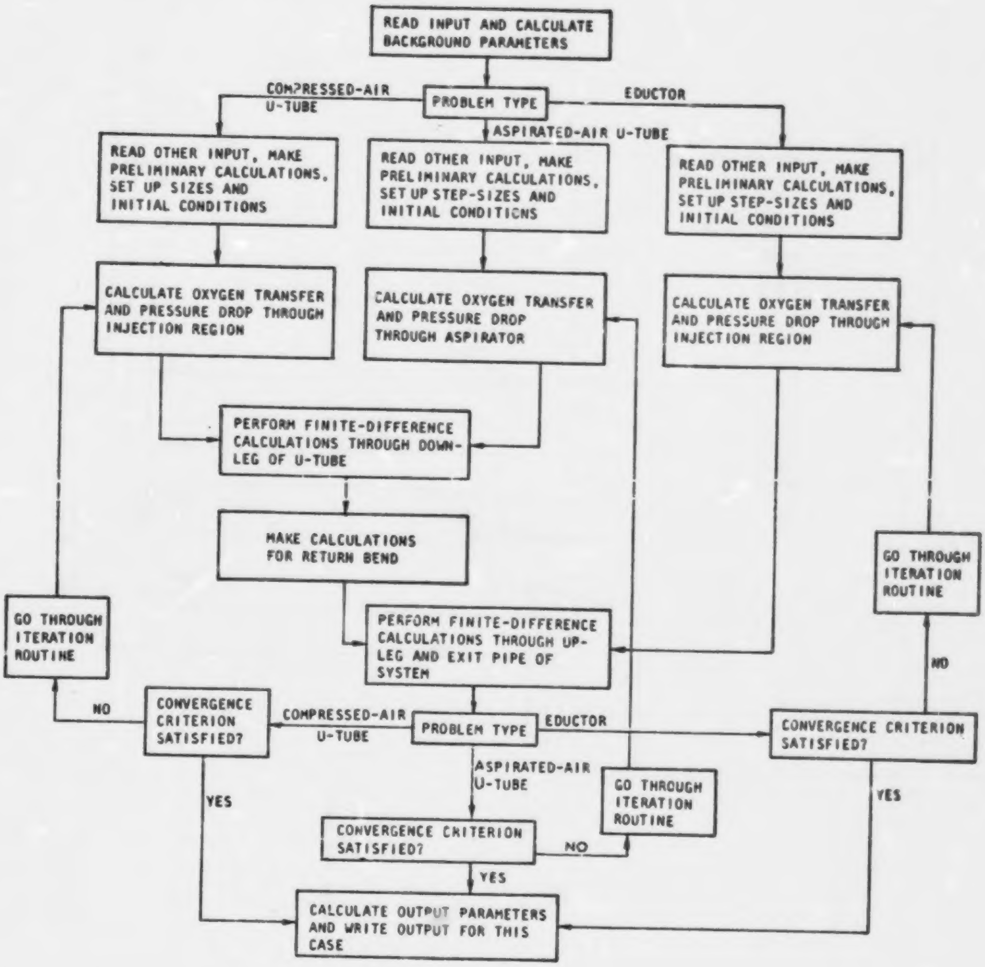
READ INPUT AND CALCULATE BACKGROUND PARAMETERS
PROBLEM TYPE
COMPRESSED-AIR U-TUBE
ASPIRATED-AIR U-TUBE
EDUCTOR
READ OTHER INPUT, MAKE PRELIMINARY CALCULATIONS, SET UP SIZES AND INITIAL CONDITIONS
READ OTHER INPUT, MAKE PRELIMINARY CALCULATIONS, SET UP STEP-SIZES AND INITIAL CONDITIONS
READ OTHER INPUT, MAKE PRELIMINARY CALCULATIONS, SET UP STEP-SIZES AND INITIAL CONDITIONS
CALCULATE OXYGEN TRANSFER AND PRESSURE DROP THROUGH INJECTION REGION
CALCULATE OXYGEN TRANSFER AND PRESSURE DROP THROUGH ASPIRATOR
CALCULATE OXYGEN TRANSFER AND PRESSURE DROP THROUGH INJECTION REGION
PERFORM FINITE-DIFFERENCE CALCULATIONS THROUGH DOWN-LEG OF U-TUBE
MAKE CALCULATIONS FOR RETURN BEND
GO THROUGH ITERATION ROUTINE
GO THROUGH ITERATION ROUTINE
PERFORM FINITE-DIFFERENCE CALCULATIONS THROUGH UP-LEG AND EXIT PIPE OF SYSTEM
NO
NO
CONVERGENCE CRITERION SATISFIED?
COMPRESSED-AIR U-TUBE
PROBLEM TYPE
EDUCTOR
CONVERGENCE CRITERION SATISFIED?
ASPIRATED-AIR U-TUBE
GO THROUGH ITERATION ROUTINE
YES
YES
CONVERGENCE CRITERION SATISFIED?
NO
YES
CALCULATE OUTPUT PARAMETERS AND WRITE OUTPUT FOR THIS CASE

Figure 46. Computation Flowsheet for Design Program

- Pipe diameters (D_1, D_6, D_9)
- System dimensions (a_{10}, a_{11}, a_{16}, a_{18}, a_{19})

A complete listing of the program, detailed instructions for preparing input data, and a sample data deck are given in Appendix C. Examples of the program output are given in Appendix D. Typical examples of parametric design trends are given later in this section.

Important Relationships and Assumptions

Most of the equations and relationships developed for the data reduction program were used as part of the design program. Equation set 23 is used for the basic numerical integration. Pressure losses are calculated using basic fluid dynamics principles plus Eq. 3 (for the aspirator), 9 (for the down-leg), and 10 through 12 (for the up-leg). Equation 19 was used to estimate mass transfer in the aspirator. Oxygen mass transfer coefficients were evaluated from Eq. 27; nitrogen mass transfer coefficients were assumed to be 0.9 times the value for oxygen at the same conditions. Equations 21 and 22 were used to represent the equilibrium gas solubility data.

U-TUBE PARAMETRIC DESIGN TRENDS

In designing a U-tube system, it is important to consider parametric trade-offs between various design variables to determine those conditions that best meet the requirements and constraints of a particular application. There are generally a large number of combinations of design parameters that will produce a given amount of oxygen transfer. The following two subsections illustrate and discuss typical effects of the major design variables on performance of compressed-air and aspirated-air U-tubes.

Design Trends for Compressed Air U-tubes

Figures 47 through 51 summarize results from a large number of calculations made with the U-tube design program. Each curve in these figures represents a series of calculation cases. The examples in this and the next subsection all have the following fixed conditions, unless otherwise specified: water flow rate, Q_W, is 5 mgd (3472 gpm); incoming water has zero dissolved oxygen (D.O.), no sulfides or rapid chemical oxygen demand, and an alpha value of 0.9; water and air temperatures are 68°F; and the ambient pressure is 1 atmosphere.

Figure 47 shows the effects of pipe diameter, as represented by the superficial water velocity. The superficial water velocity is defined as the mean velocity with which the specified water flowrate (in this case 3472 gpm) would flow if no air were present. As the water velocity is increased (pipe diameter is decreased) the exit D.O. concentration decreases and the pressure drop increases. Therefore, the operating cost is minimized by making the pipe diameter as large as practical;

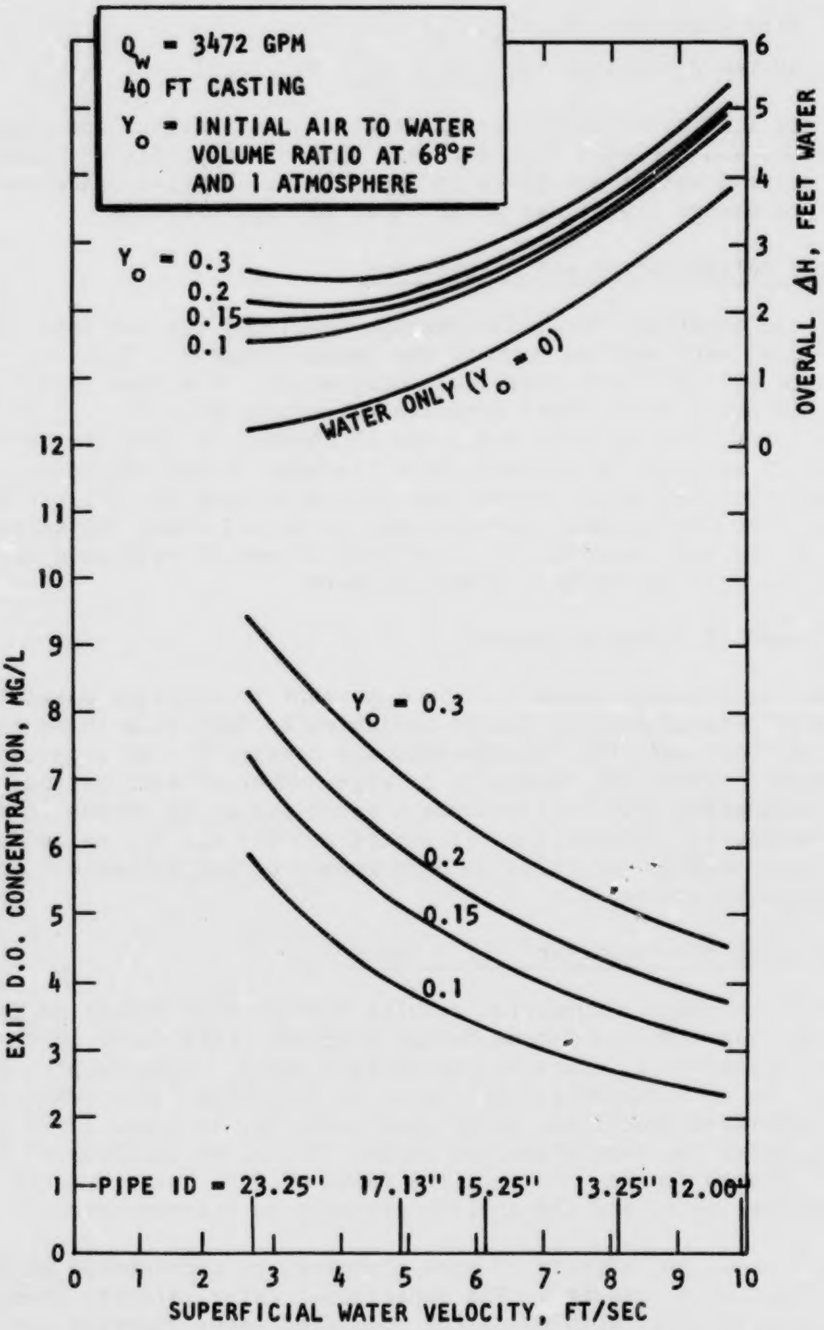

Figure 47. Effect of Pipe Size on Performance of Compressed-Air U-Tubes

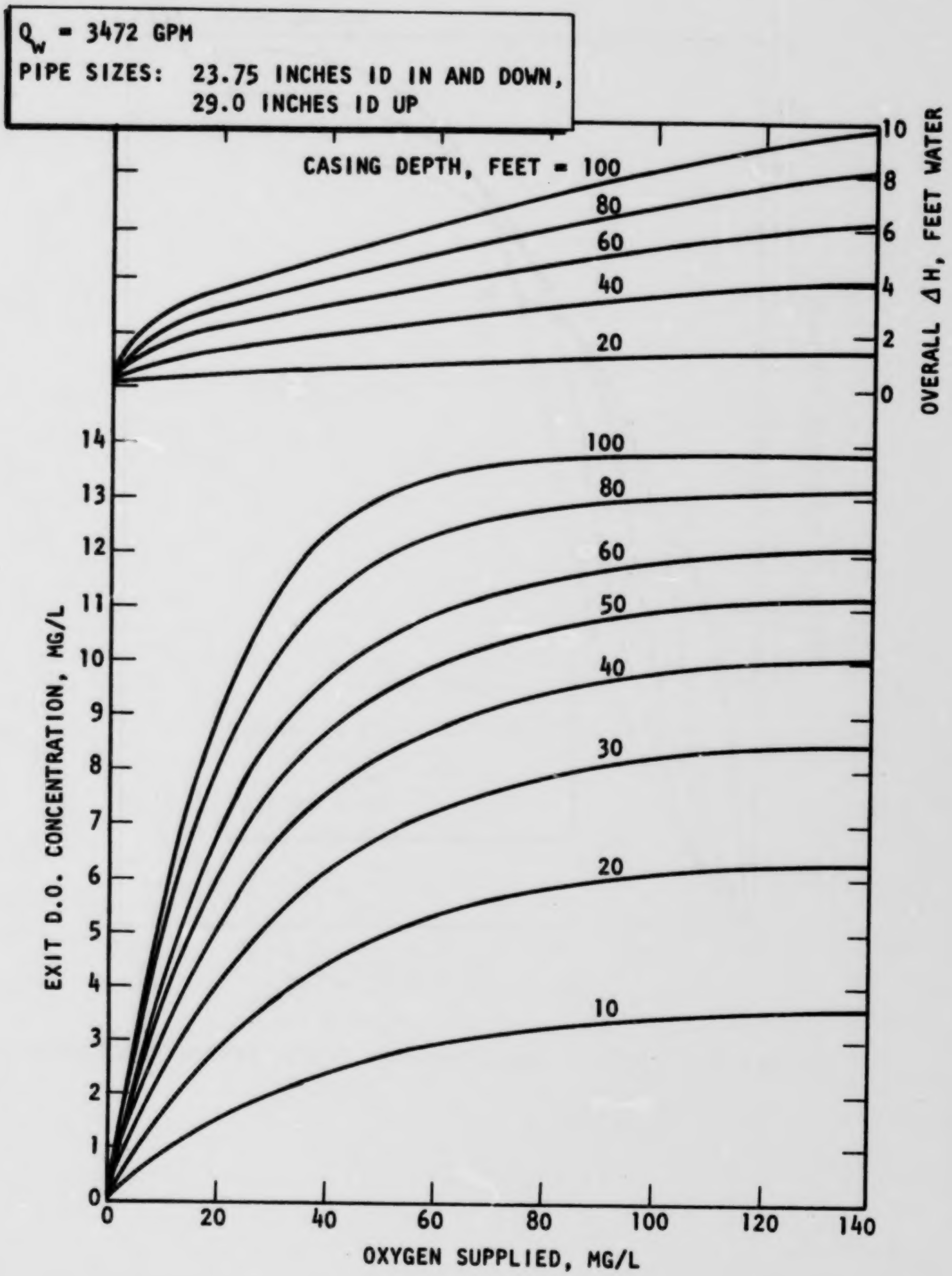

Figure 48. Typical Compressed-Air U-Tube Parametric Designs

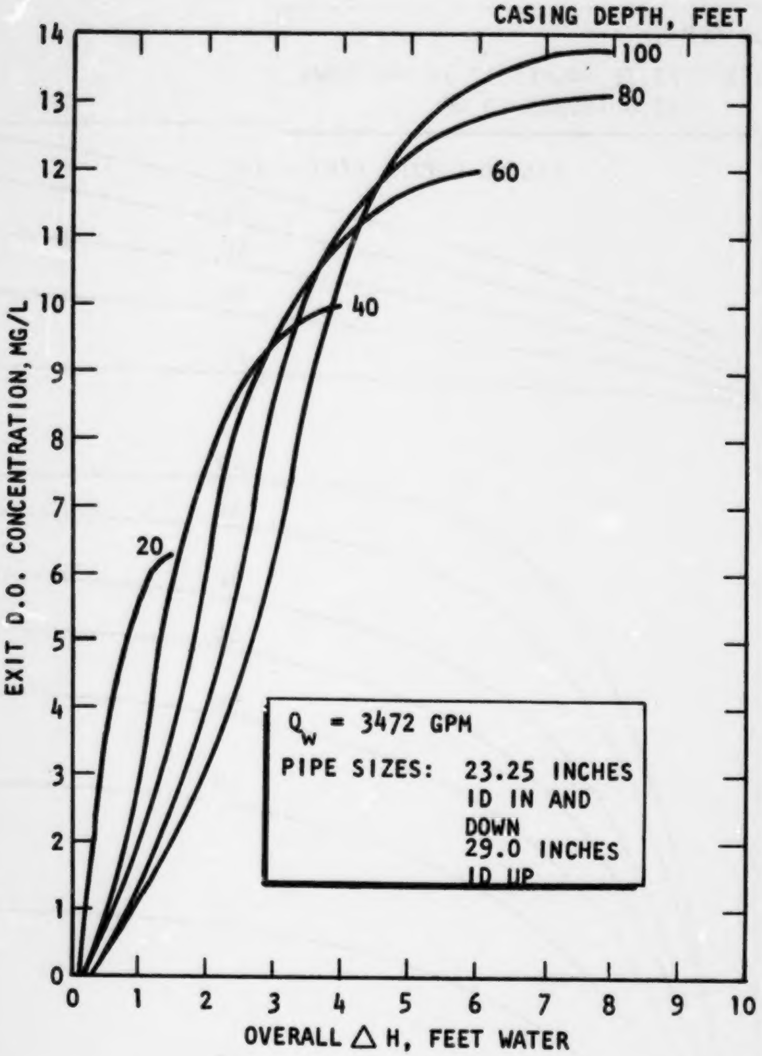

Figure 49. Typical Compressed-Air U-Tube Design Trade-Offs

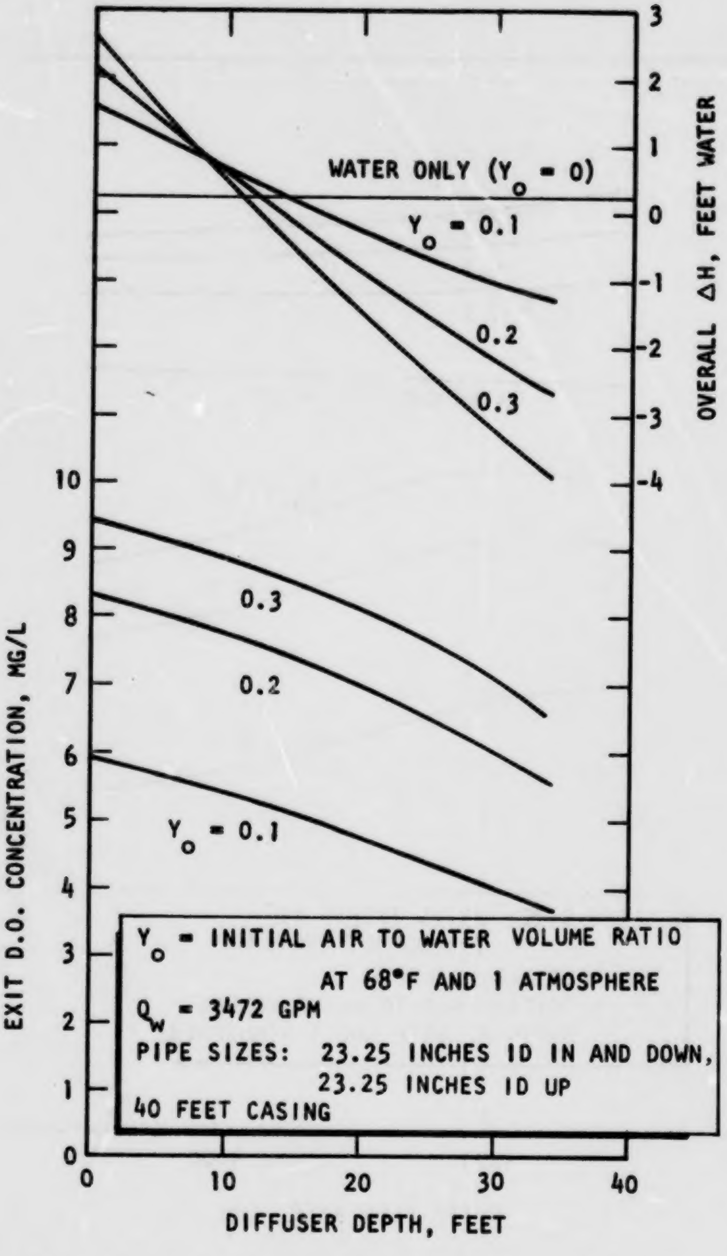

Figure 50. Effect of Diffuser Depth on Performance of Compressed-Air U-Tubes

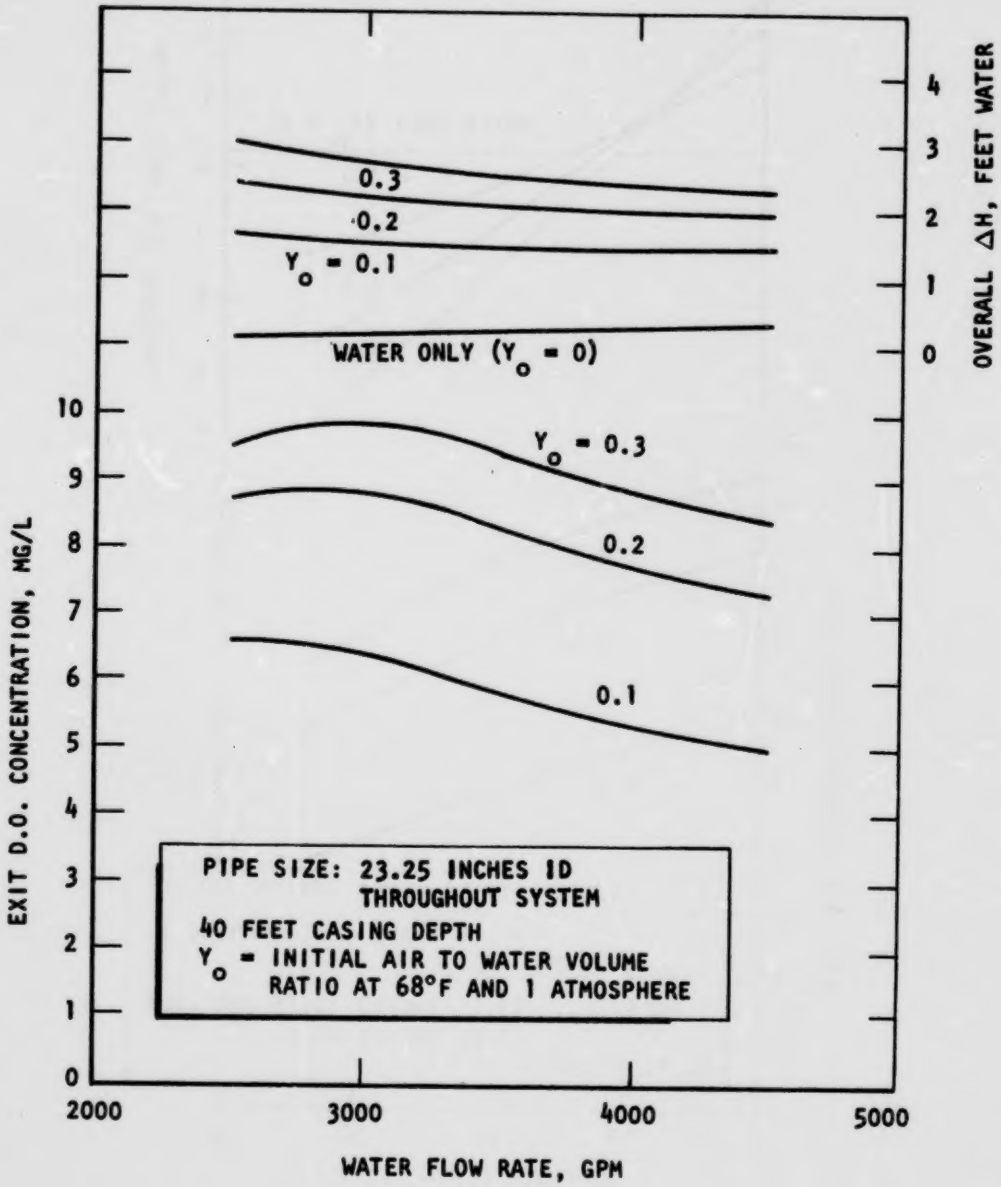

Figure 51. Effect of Water Flow Rate on Performance of Compressed-Air U-Tubes

however, this will also increase the capital cost. In each design study, there should be made trade-offs between operating and capital cost, taking into account the constraints and priorities of the particular case. The lowest practical superficial water velocity in the down-leg is of the order of 2 ft/sec, and each case should be checked to avoid slug flow and other difficulties in the down-leg. The up-leg velocity may have to be at least 3 to 5 ft/sec if there is appreciable silt.

Figure 48 displays predicted performance trends for what are probably the largest pipe sizes that could even be considered for this case: 23.25-inch I.D. (24-inch schedule 20 pipe) for the down-leg, and 29.00-inch I.D. (30-inch schedule 20 pipe) for the up-leg. The superficial water velocities are 2.62 and 1.69 ft/sec, respectively. This series of curves displays the effects of two important independent variables: amount of oxygen in air supplied, and U-tube depth, expressed as the depth of a casing containing the U-tube (which is 0.5 foot shorter than the casing) on the two primary dependent variables or performance parameters: exit dissolved oxygen concentration (all inlet oxygen concentrations are zero for standardization) and total pressure drop across the U-tube system. The two quantities used in this report to express the relative amounts of air and water are directly related by the expression:

$$\text{Oxygen supplied, mg/l} = 280\ \begin{array}{l}\text{(air-to-water volume ratio at 68°F,}\\ \text{1 atmosphere)}\end{array}$$

It can be seen in Fig. 48 that both the D.O. concentration and pressure drop increase with increasing air rate (shown as mg/l of oxygen supplied) and with increasing U-tube depth. Each performance variable increases at a rate less than linear (i.e., has a negative second derivative), and the exit D.O. concentration particularly levels off as high amounts of oxygen are supplied. This region of diminishing returns should be expected; when very large amounts of oxygen are present. the oxygen utilization is less efficient. For reference, it might be noted that the saturation concentration of dissolved oxygen at 68°F and in contact with normal air at 1 atmosphere pressure is 9.08 mg/l. Therefore, it is seen that the effluent water can be supersaturated for a considerable range of higher air rates and deeper U-tubes.

To more clearly visualize the trade-offs between exit D.O. concentration and pressure loss, the parametric results of Fig. 48 were cross-plotted in Fig. 49, in which the amount of oxygen supplied is an implicit parameter. It can be observed that the required pressure loss for an incremental increase in exit D.O. concentration becomes relatively greater as the exit D.O. level increases. It is also interesting to examine the crossing-over of the curves for various U-tube depths. One conclusion which can be drawn is that a deeper U-tube does not necessarily result in improved performance. For example, at a fixed overall pressure drop of 3 ft water, the exit D.O. concentrations for 40, 60, 80, and 100 feet casings are 9.5, 9.6, and 6.2 mg/1, respectively. However, it should be further noted that the amount of air which must be added is much less for the deeper U-tubes; the values (see Fig. 48) corresponding to these four points are about 79, 39, 21, and 12 mg/1 for 40, 60, 80, and 100 feet casings. Another observation which can be made from both Fig. 48 and 49 is that there are almost asymptotic upper limits on the exit D.O. concentration that can be obtained from a U-tube of a particular depth; e.g., if an exit D.O. concentration of 7 mg/1 is desired for a design point, it is essentially impossible to reach this with a 20-foot U-tube, probably inefficient to accomplish it with a 30-foot U-tube, and begins to be more efficient for U-tubes of 40 feet or more in depth.

All of the parametric curves discussed so far were for cases with the air diffuser ring mounted at the top of the down-leg (i.e., a_{25}, shown in Fig. 45, is zero). Figure 50 shows the effect of lowering the elevation of the diffuser ring (i.e., increasing the diffuser depth, a_{25}) on the two major performance variables, for several values of y_o. As the diffuser ring elevation is lowered, the pressure drop across the U-tube is decreased, eventually becoming negative (i.e., there is a net pressure increase across the U-tube due to the air-lift effect). This effect is not gained without cost, however. The exit D.O. concentration decreases (because the air is in contact with the water during only a portion of the U-tube) and also the required air pressure increases, since it must be injected at a region of higher water pressure. A value of a_{25} equal to about 34 feet corresponds to having the diffuser ring at the bottom of the down-leg (since about 6 feet of the 40-foot casing depth is taken up by two L.R. elbows. (In practice, S.R. or special elbows would probably be used for pipe this large.) In this extreme case, the compressed-air U-tube is essentially an eductor, and the pressure increase (air lift) is nearly 4 feet of water for $y_o = 0.3$.

From various parametric studies, it appears that it will generally be preferable to design for the diffuser ring at the top of the down-leg; however, the design flexibility offered by allowing this location to vary may be of value in some cases, e.g., those in which no net pressure drop across the system can be allowed.

Figure 51 illustrates the effect of changing the water flow rate on a fixed U-tube design. The major point of these curves is to illustrate the flexibility of a compressed air U-tube. For example, if the design point were $Q_w = 3000$ gpm and $y_o = 0.3$, the exit D.O. concentration and pressure drop would be about 9.9 mg/1 and 2.8 feet of water. If the water flow rate were increased to 4500 gpm and if the air flow rate were also increased to maintain a y_o of 0.3, the concentration and pressure drop would be about 8.4 mg/1 and 2.4 ft water. If the air flow rate were maintained at the original level, thus giving a y_o of 0.2 at $Q_w = 4500$ gpm, the concentration and pressure drop would be about 7.3 mg/1 and 2.0 feet of water.

Design Trends for Aspirated-Air U-Tubes

This subsection illustrates and discusses typical effects of the major design variables on performance of aspirated-air U-tubes. Figures 52 through 56 summarize results from a large number of calculations made with the U-tube design program. Each curve in these figures was constructed from the results of a series of calculation cases. The following conditions were held fixed (the same conditions were used in the compressed-air examples given in previous subsection), unless otherwise specified: water flow rate, Q_w, is 5 mgd (3472 gpm); incoming water has zero D.O., no sulfides or rapid chemical oxygen demand, and an alpha value of 0.9; $a_{18} = 2$; $a_{19} = 8$ ft (drop in elevation between inlet and outlet pipes); water and air temperatures are 68°F; and the ambient pressure is 1 atmosphere.

Figure 52 displays the effects of U-tube depth and amount of oxygen supplied on the two primary performance variables (exit D.O. concentration and overall pressure drop) and on the required aspirator contraction area ratio, E (defined as the entrance pipe cross-sectional area divided by the throat cross-sectional area). Curves for each of these three variables are shown as a function of the amount of oxygen supplied (i.e., the amount of oxygen in the air which is aspirated into the flowing water stream), and for six casing depths (which are about 0.5 foot greater than the U-tube depth). For lower amounts of oxygen supplied, it would be possible in this case to aspirate without a venturi (i.e., E=1). This is a result of the value of a_{19}, which produces a siphon effect. As the desired amount of oxygen to be supplied (or exit D.O. concentration) is increased, it becomes necessary to constrict the throat cross-sectional area (i.e., include a venturi). This results in an increase in exit D.O. concentration, but also produces a substantial increase in pressure loss.

This is caused by a major constraint that is characteristic of any aspirated air U-tube: the aspirator must cause enough local acceleration of the fluid to reduce the pressure at the aspirator throat to less than the ambient air pressure, to aspirate air into the flowing water stream. This is not particularly difficult in a gravity-flow system where the pressure at the entrance to the aspirator is merely due to the height of liquid above it. In a force-main application, however, the design is more difficult because the aspirated entrance pressure can be considerably greater than the ambient pressure. If the pressure downstream of the aspirator (p_5 - p_{12} using the station numbers shown in Fig. 44) is substantial, the aspirator contraction ratio must be much larger (i.e., throat smaller) than for a corresponding gravity flow application. This in turn, leads to a higher value of R (pressure drop across the aspirator divided by equivalent one-phase pressure drop from aspirator entrance to throat), since R increases with increasing venturi contraction area ratio. This "magnification effect" does cause a rapid increase in pressure loss across a U-tube in a force main for small throat cross-sectional areas (high values of E). This is a very important design consideration, and it imposes more restrictive constraints (and generally results in a higher overall head loss) on a design for an aspirated-air U-tube in a force main than for as aspirated-air U-tube in a gravity flow line, or for a compressed-air U-tube in either type of application. It is generally uneconomical to select a design point which falls very far into the high slope portion of the ΔH curve (e.g., 70 mg/l oxygen supplied for a 40-ft casing, as shown in Fig. 52).

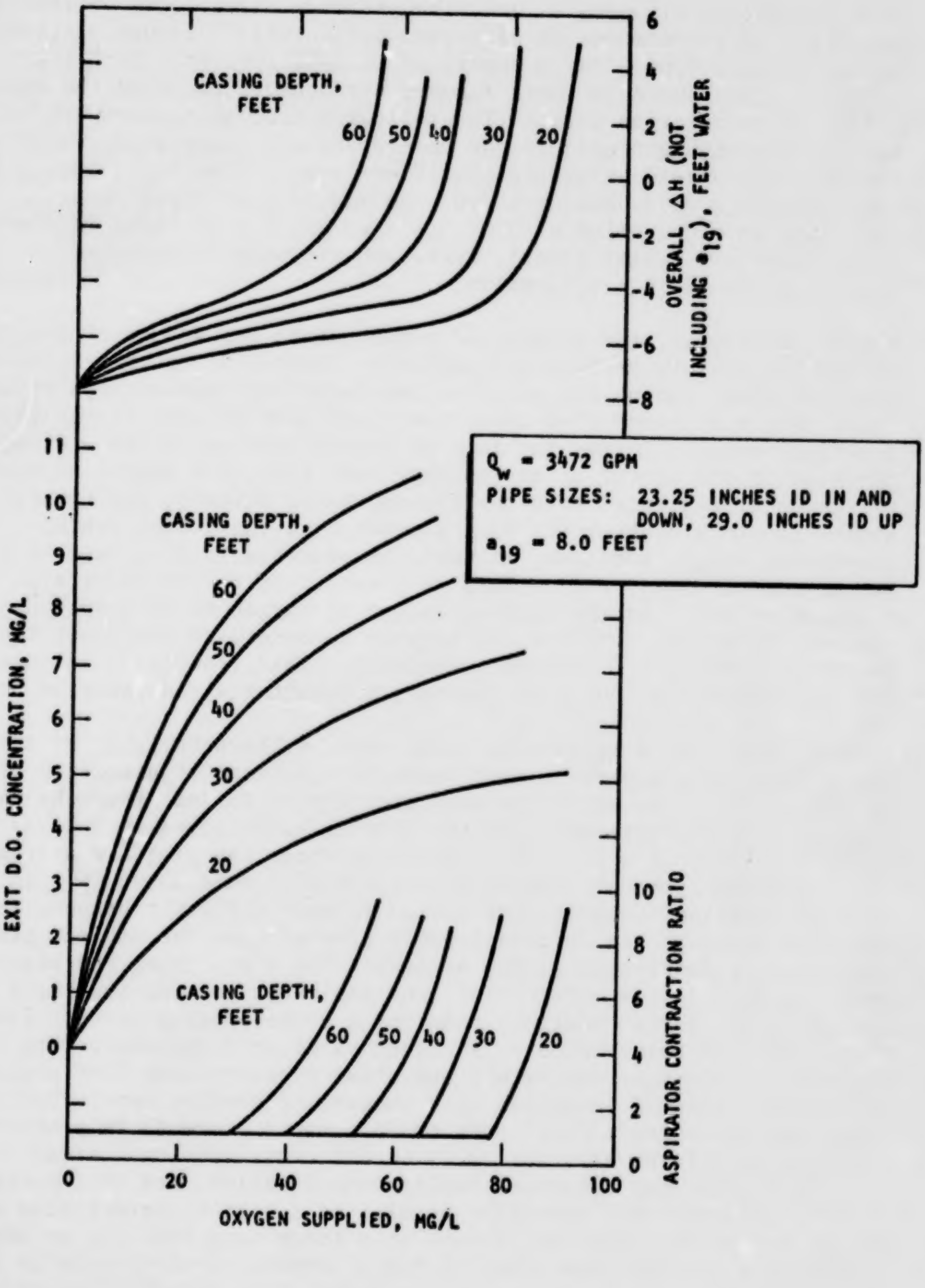

Figure 52. Typical Aspirated-Air U-Tube Parametric Designs

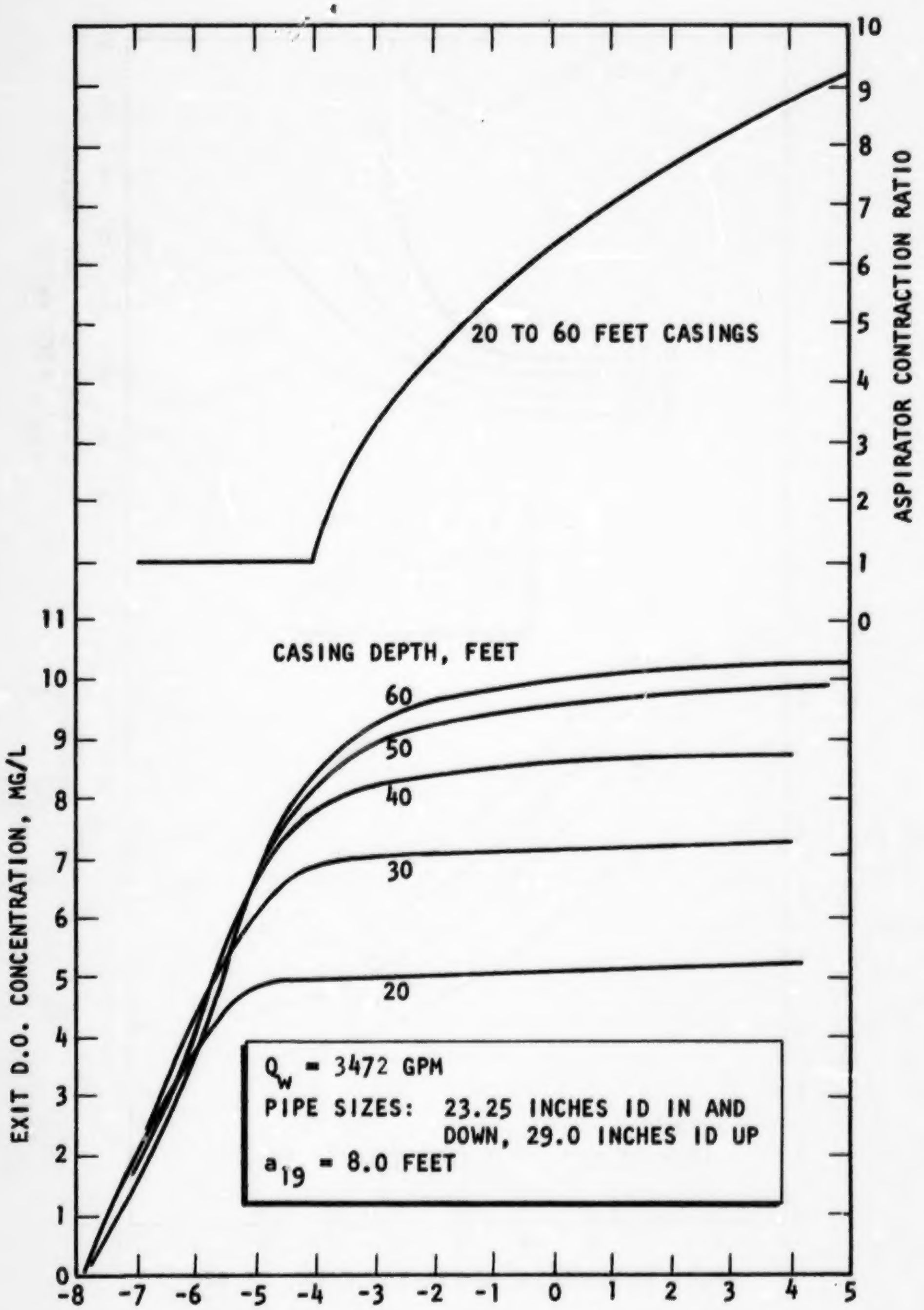

Figure 53. Typical Aspirated-Air Design Trade-Offs

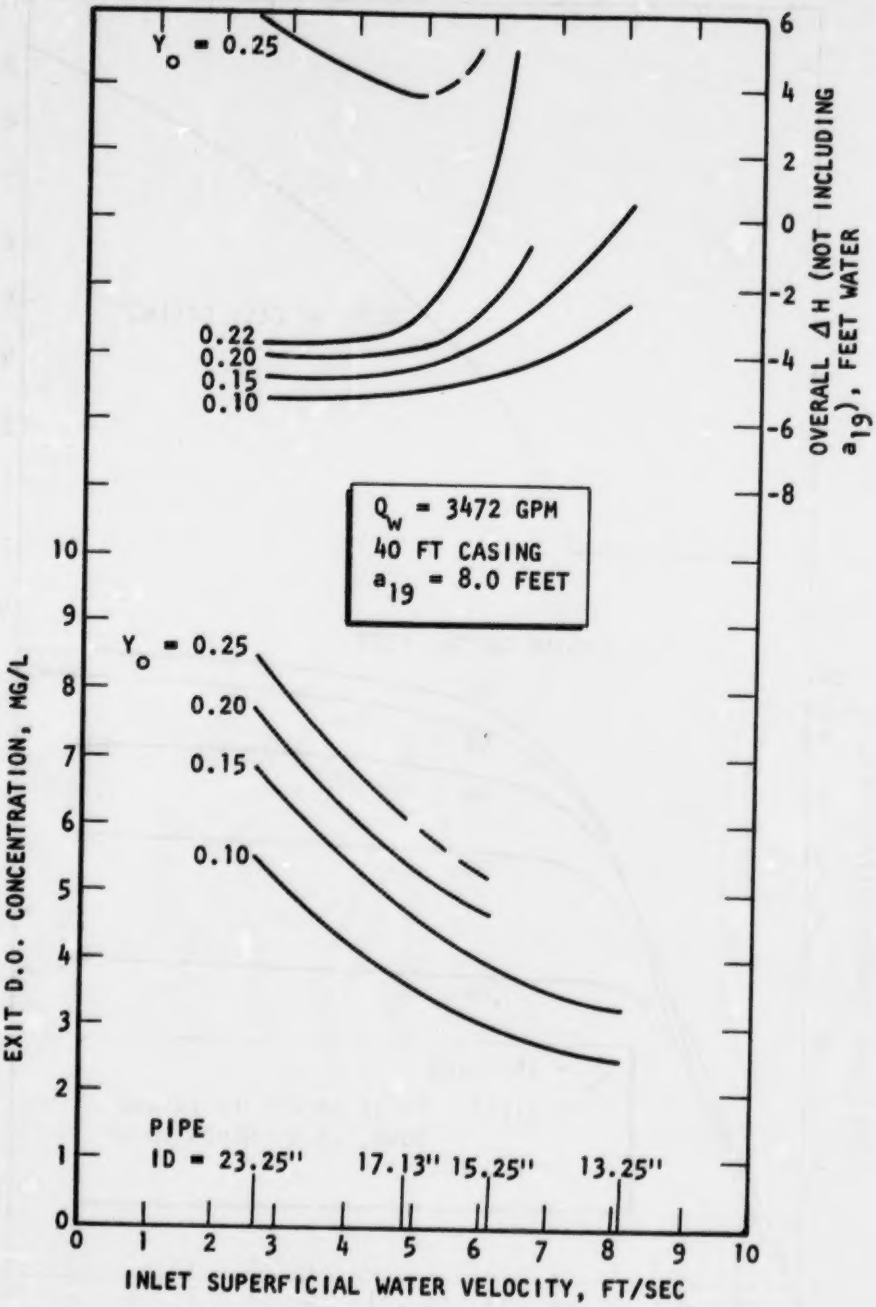

Figure 54. Effect of Pipe Size on Performance of Aspirated-Air U-Tubes

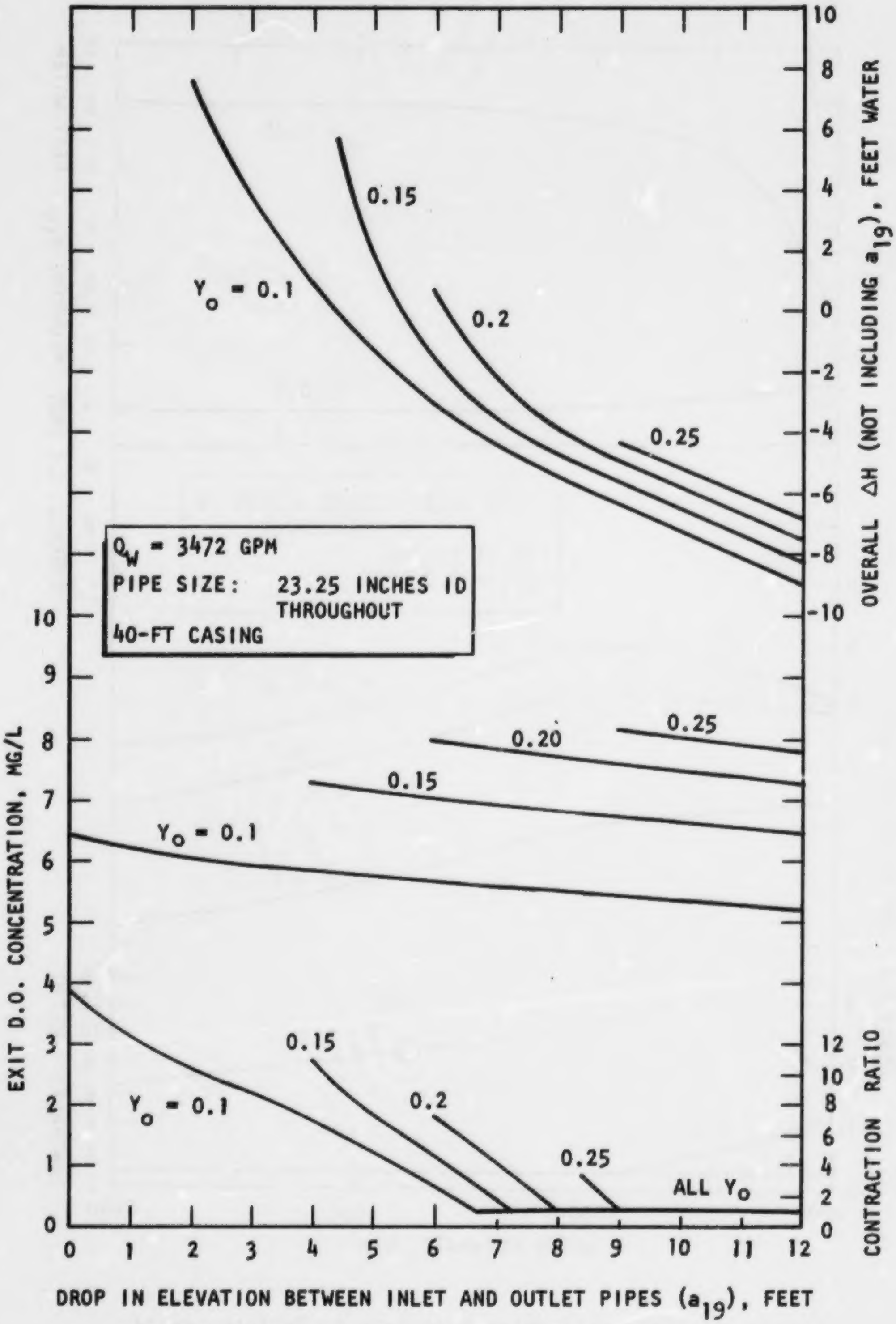

Figure 55. Effect of Inlet and Exit Pipe Elevations on Performance of Aspirated-Air U-Tubes

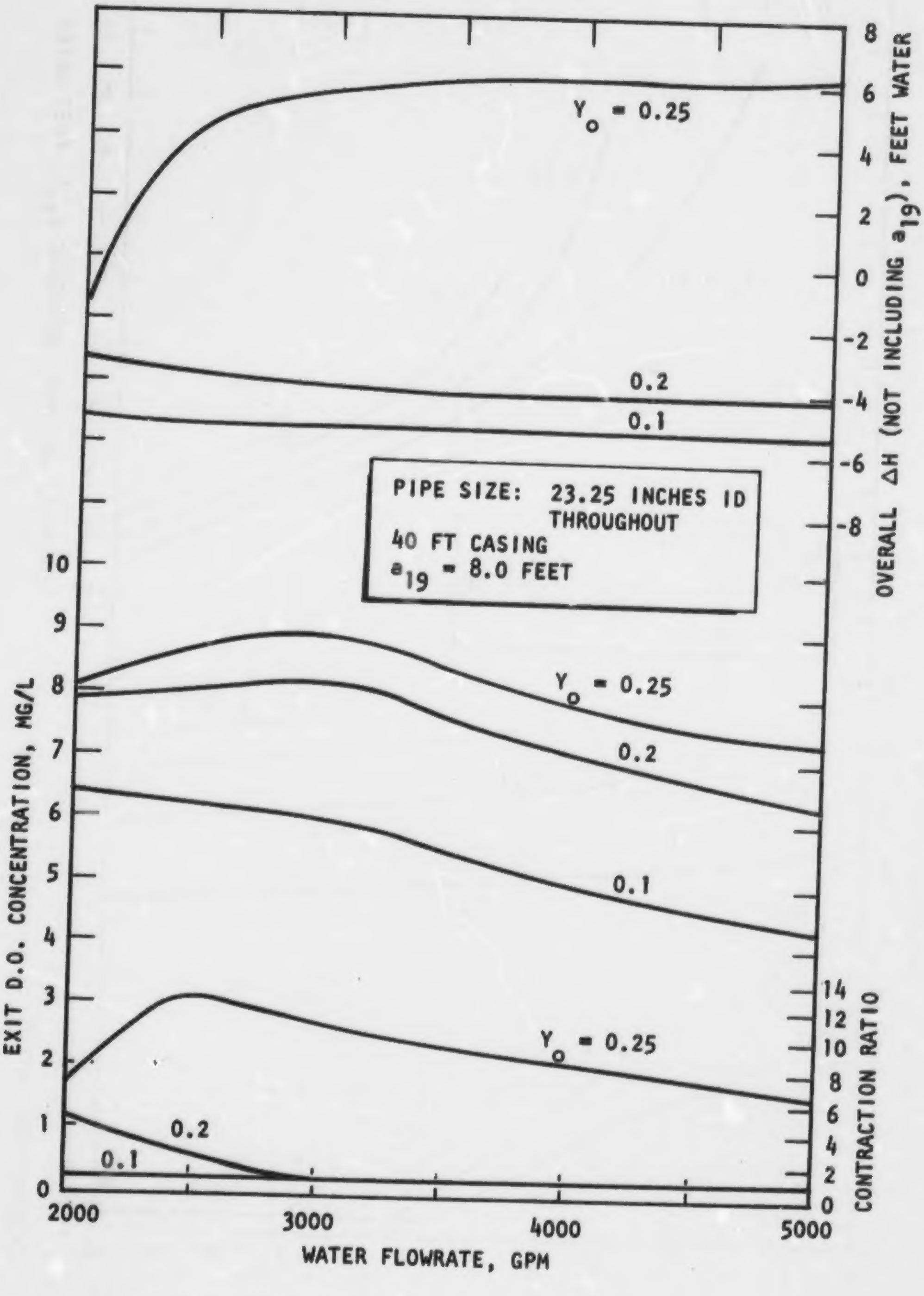

Figure 56. Effect of Water Flow Rate on Performance of Aspirated-Air U-Tubes

Figure 53 is analogous to Fig. 49 for compressed-air U-tubes, and represents a cross-plot of the data in Fig. 52, in which the amount of oxygen supplied is an implicit parameter. Many of the parametric trends are similar; however, several substantial differences can be noted. There is a more pronounced effect of U-tube depth on the trade-off curves for aspirated air than for compressed-air U-tubes. The cross-overs in the curves for various depths are less pronounced and occurs at lower values of air-to-water ratio than for compressed-air U-tubes. Consequently, the efficiency of aspirated-air U-tubes is almost always better as the depth increases, for practical ranges of air-to-water ratio. Such improvements in operating performance must be balanced against the increased capital cost of deeper U-tubes, however.

The effects of pipe diameter, as represented by the superficial water velocity, are shown in Fig. 54. It is interesting to note that the total pressure drop curves for higher values of y_o pass through pronounced minimums as the velocity is changed. This behavior is somewhat different from that predicted for compressed-air U-tubes (Fig. 47). The primary reason for the minimum in the aspirated-air cases is that the higher velocities make it possible to aspirate with a smaller value of E, thereby effecting a substantial decrease in system pressure drop. This saving initially overcomes the increase in pressure drop across the aspirator, as the velocity is increased, although the latter eventually becomes the more dominant factor, hence causing the ΔH curves to turn upward again. The large difference in ΔH between $y_o = 0.22$ and 0.25 is caused by the rapid increase in E in this region. For example, with 23.25-inch ID pipe, $E = 1.89$ at $y_o = 0.22$ and $E = 9.65$ at $y_o = 0.25$.

Aspirated-air U-tubes do not have as much design flexibility as is available for compressed-air U-tubes. One of the major differences is that it is not practical (or of any advantage) to install the air injection location for aspirated-air U-tubes at different elevations in the down-leg, as was illustrated for compressed-air U-tubes in Fig. 50. However, in some cases, it is possible to arrange to have the elevation of the exit pipe (station 11 to 12 in Fig. 44) lower than the elevation of the aspirator (i.e., to have $a_{18} + a_{19}$ greater than zero). Because of the "magnification effect" in aspirator characteristics, discussed earlier in this subsection, modest differences between these two elevations can have a very substantial effect on the performance of an aspirated-air U-tube, as illustrated in Fig. 55. The exit D.O. concentration is affected very little by increasing a_{19}; however, the pressure drop across the system is reduced substantially. If a_{19} is made large enough, it is possible to reduce ΔH to zero or below. It should not be concluded that this improvement is obtained without cost--there must be a difference in elevation; however, if this is available or can be provided easily, then this is a very important direction for optimization in a particular aspirated-air U-tube design.

Figure 56 illustrates the effect of changing the water flow rate on parametric U-tube designs in which all geometry variables are fixed except for the aspirator contraction ratio, which is changed as necessary. It can be seen that there is considerable flexibility in design without the need to change pipe size.

ECONOMIC COMPARISONS

Results of preliminary economic comparisons between U-tube systems and current conventional aeration methods are described. Comparisons are made for two major applications: Postaeration of treated waste water effluent, and *in situ* aeration of sanitary sewers. The predesign cost estimates were made, in most cases, without the benefit of firm pricing based upon detailed designs and, consequently, do not establish the absolute costs of the processes. However, these estimates given an approximate value of costs to be expected, in addition to the primary purpose of comparing the cost of U-tube aeration with costs for various other aeration systems.

Postaeration of Treated Effluent

Two commonly used systems, diffused air and mechanical aeration, were selected for economic comparisons with U-tube aeration. A prime consideration for diffused aeration is the type of diffuser to be used. Choice of an air diffuser on the basis of oxygen transfer efficiency (oxygen dissolved/oxygen supplied) alone would lead to use of small bubble diffusers such as porous tubes (Ref. 26 and 27). However because of the higher pressure and maintenance requirements for small bubble diffusers, spargers were selected as the diffuser type for this comparison. Plug flow (i.e., no mixing in the direction of flow) was assumed for the aeration tanks, since this would result in higher driving forces for mass transfer and, consequently, lower costs than for other conventional flow assumptions.

Mechanical or entrainment-type aerators employ some type of circular, rotating element, such as a plate with vertical blades or inclined vanes extending from the periphery of the plate. The element typically rotates in a horizontal plane a short distance below the water surface, and air is entrained by the moving blades of the turbine. Although other types of mechanical aerators have been described, this basic type of design was selected for this study.

U-tube aeration systems might have several configurations, as previously discussed. However, for comparable in-tube velocities, air-to-water ratios, and depth, all configurations should perform essentially the same with respect to oxygen transfer. Two types of U-tube configurations were chosen for these comparisons: (1) concentric circular pipes with flow downward through the inside pipe and upward through the annulus, and (2) a wide rectangular trench with a vertical flat partition extending across the width to divide the trench into two passages--with the water flowing downward through one passage, under the bottom edge of the partition, and upward through the other passage so formed.

The aeration systems were considered as an extension of an existing plant and secondary effluent discharge channel. Typical system layouts are illustrated by Fig. 57 and 58, although the specific details were varied to result in low-cost systems for the various flowrates and amounts of dissolved oxygen to be added. The principal design and cost bases, which were assumed or established from the preliminary design studies, are given in Table 5.

Performance data for diffused air and mechanical aeration systems at standard conditions (i.e., for tap water at 20°C., 1 atmosphere, containing no dissolved oxygen, and with $\alpha = 1.0$) were adjusted to the conditions given in Table 5 with the relationship

$$N = \frac{N' \alpha \, (1.024)^{T-20} (D_1 - D_2)}{C_s' \ln (D_1/D_2)} \tag{28}$$

where N is the aerator performance rating (e.g., in lb oxygen/hp/hr), superscript prime refers to standard conditions, and subscripts 1 and 2 refer to initial and final conditions, respectively. This expression was used to calculate the efficiencies of a turbine-type aerator and a sparger at several levels of final D.O. content. Performance ratings at standard conditions (14.7 psia, 68°F, $\alpha = 1$) from Ref. 28, 29, and 30 are shown in Fig. 59 along with the efficiency curves for the two aeration methods. Mechanical aerators typically have higher-power performance ratings (N) than diffused air systems; however, they also have higher capital, operating, and maintenance costs.

After selecting up-leg and down-leg velocities plus casing diameters, the U-tube depth was optimized. Optimization consisted of deriving operating lines (based on the computer printouts) of the form shown in Fig. 60 for various casing depths ranging from 20 to 70 feet. For selected exit D.O. levels, each casing depth gave an associated U-tube plus the power required to pump the flow at a given ΔH was evaluated for each casing depth at a given exit D.O. An optimum casing depth (corresponding to optimum cost) was selected at several exit D.O. levels. Values of some of the important system characteristics are given in Table 6 for three values of final dissolved oxygen concentration.

The major constituents of the physical plant costs are listed in Table 7. Major equipment costs such as mechanical aerators, pumps, and motors were based on manufacturers' quotes. Estimates of concrete construction, air and water piping, excavation, and other similar costs were obtained from standard sources of cost data (Ref. 31 and 32). Factors such as maintenance, operating labor, power, plant overhead, and administrative costs were also considered in the total estimates.

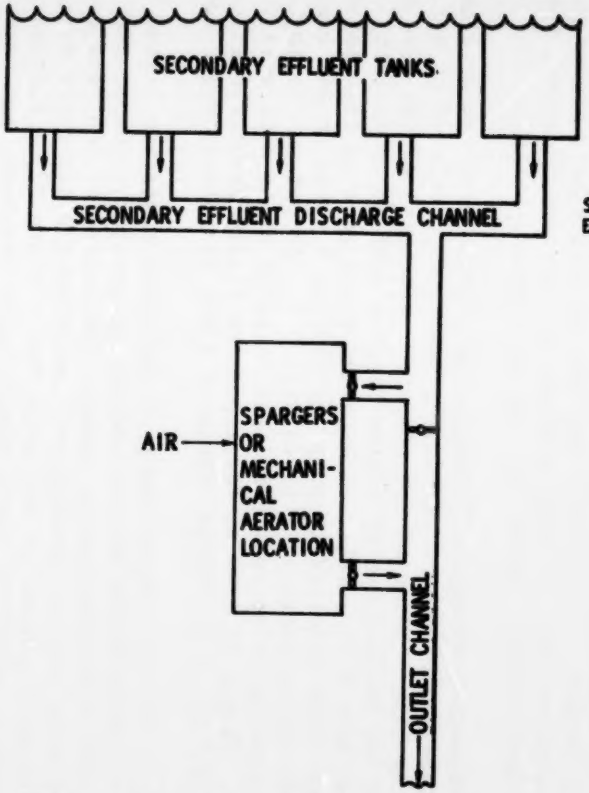
SECONDARY EFFLUENT TANKS
SECONDARY EFFLUENT DISCHARGE CHANNEL
AIR
SPARGERS OR MECHANICAL AERATOR LOCATION
OUTLET CHANNEL

Figure 57. Schematic Layout of Postaeration Facility

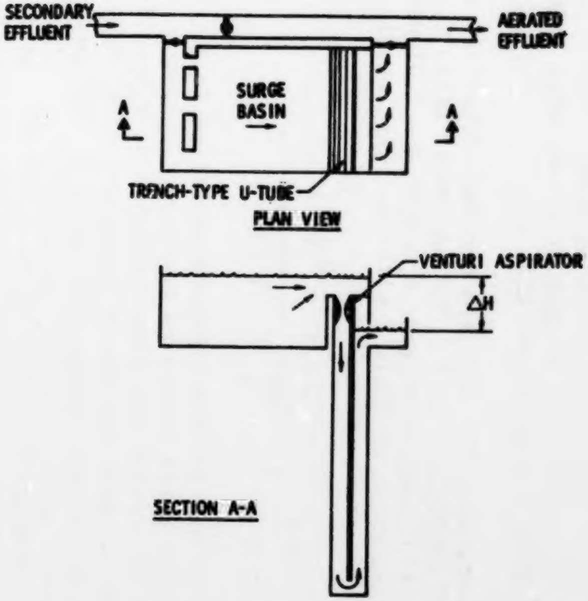
SECONDARY EFFLUENT
AERATED EFFLUENT
SURGE BASIN
A
A
TRENCH-TYPE U-TUBE
PLAN VIEW
VENTURI ASPIRATOR
ΔH
SECTION A-A

Figure 58. Schematic Layout of U-Tube Facility

TABLE 5. SELECTED ECONOMIC AND PHYSICAL DESIGN BASES FOR POSTAERATION SYSTEM COST ESTIMATES

1. Aeration plant flowrates of 10 mgd and 100 mgd
2. Aeration installation is immediately downstream of the treatment plant, and laboratory facilities, proximate utilities, and buildings are available.
3. Water temperature is 75°F.
4. Ambient pressure is 14.5 lb/sq in. abs.
5. D.O. saturation level is 8.33 mg/liter.
6. Incoming waste water (secondary treatment plant effluent) has 1.0 mg/liter D.O.
7. $\alpha = \frac{\text{Oxygen transfer rate in effluent}}{\text{Oxygen transfer rate in tap water}} = 0.90$
8. Capital costs amortized at 4.5% over 25 years
9. Electrical power cost = $0.01/kw-hr
10. Cost of land = $5000/acre
11. Total direct plant costs (including contractor, engineering, and legal fees) = 1.35 times physical plant cost

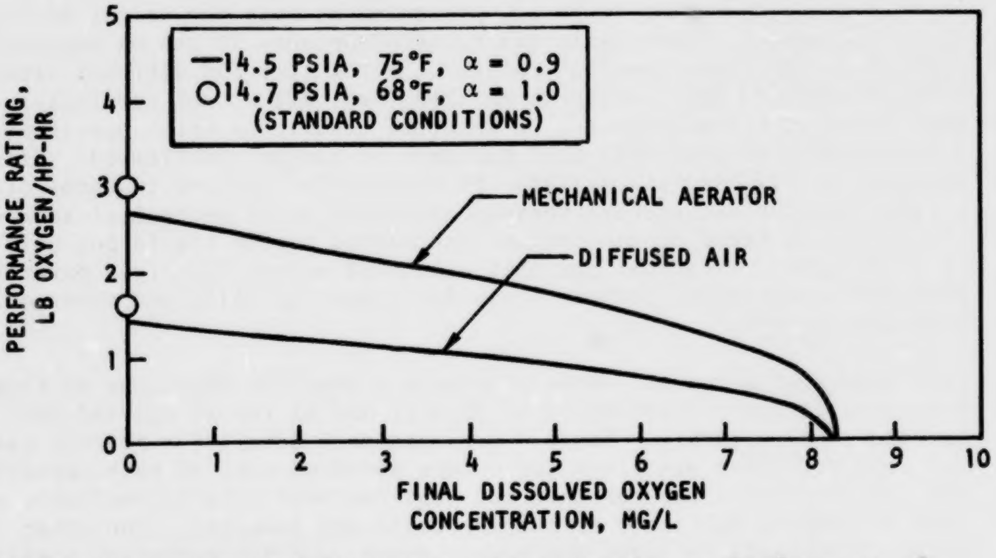

Figure 59. Effect of Final D.O. Concentration on Performance of Diffused Air and Mechanical Aeration Systems

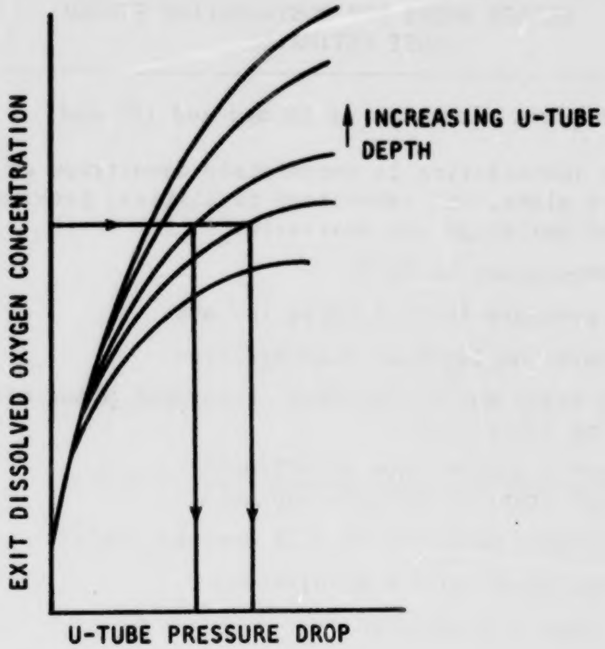

Figure 60. Schematic Diagram of U-Tube Operating Lines

In this study, aeration costs are presented as cost per weight of dissolved oxygen. This basis was selected because it can be readily applied to all three aeration systems. Mechanical and diffused aeration systems are not readily comparable (Ref. 27) except for individual cases on a realistic set of selected conditions which permit a determination of the total cost per unit of oxygen transferred. Efficiencies of diffused air systems are customarily defined in terms of oxygen transfer efficiency, whereas efficiencies of mechanical aerators are stated in terms of the oxygen transferred to the liquid per unit of power input. The cost per unit weight of oxygen dissolved parameter provides a meaningful, common basis for comparing different types of aeration systems.

Cost comparisons for all three systems are shown as functions of final dissolved oxygen concentration in Fig. 61 and 62 for 10 mgd and 100 mgd flow, respectively. Table 8 presents more detail for several cases. Two sets of values are given for U-tube aeration cost at each capacity. One (ΔH available) assumes that the required head loss is available and that no pumping equipment or pumping costs are incurred. The other curve (ΔH pumped) includes the power, pumps, and all equipment needed to supply the required head loss. If it is desired to convert these

TABLE 6. CHARACTERISTICS OF POSTAERATION SYSTEMS

	Final Dissolved Oxygen Concentration, % Saturation		
	30	60	90
10 mgd			
Dissolved oxygen input rate, lb/day	125	330	540
Air input rate for diffused air aeration, scfm	130	350	570
Tank size for diffused air aeration, feet depth x width x length	8x10x31	8x10x38	8x10x45
Tank size for mechanical aeration, feet depth x width x length	7x10x20	7x20x30	7x25x30
Number of U-tubes	2	2	2
Depth of U-tubes	20	45	60
Type of U-tube configuration	Concentric pipes		
100 mgd			
Dissolved oxygen input rate, lb/day	1250	3300	5400
Air input rate for diffused air aeration, scfm	580	1560	2540
Tank size for diffused air aeration, feet depth x width x length	15x24x50	15x24x58	15x24x66
Tank size for mechanical aeration, feet depth x width x length	7x30x35	7x30x50	7x50x90
Number of U-tubes	2	2	2
Depth of U-tubes	20	45	60
Type of U-tube configuration	Trench-type with rectangular flow cross section		

TABLE 7. MAJOR COMPONENTS IN PHYSICAL PLANT COSTS

- Land
- Excavation
- Utilities
- Aeration tank or surge tank
- Channels, flow gates, and wiers to connect to existing effluent channels
- Aeration device
- Pumps and motors (where applicable)
- Air compressor and piping (diffused air only)
- Installation

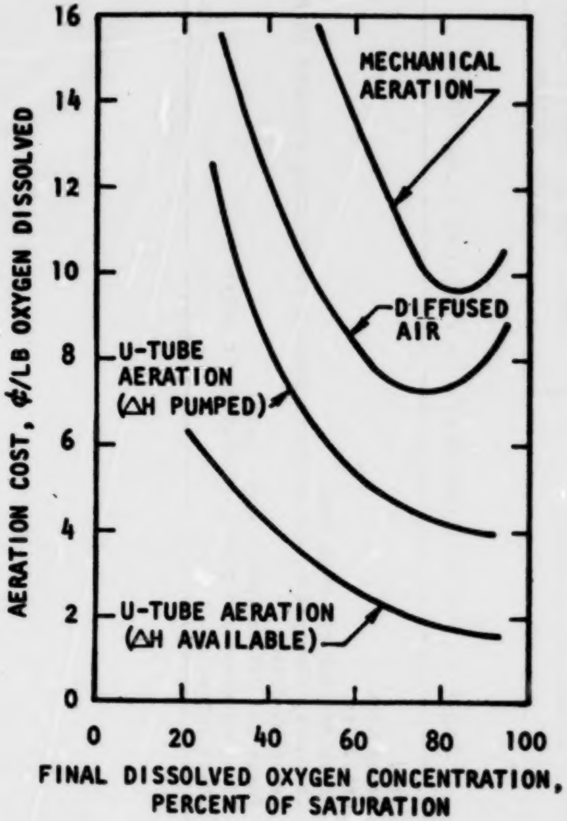

Figure 61. Cost Comparison (10 mgd)

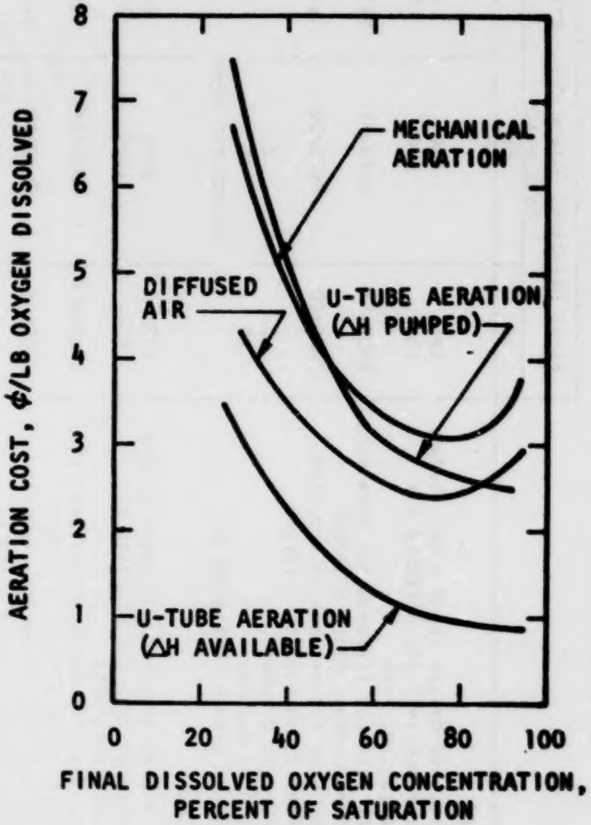

Figure 62. Cost Comparison (100 mgd)

TABLE 8. COST COMPARISON FOR POSTAERATION OF TREATED EFFLUENT

Total flow rate, 10^6 gal./day	Exit D.O. concentration % saturation	Cost component	Aeration cost, cents/lb. D.O.			
			U-tube (ΔH available)	U-tube (ΔH pumped)	Diffused air aeration	Mechanical aeration
10	30	Amortized capital	2.2	3.6	5.4	6.4
		Maintenance	0.9	2.5	2.9	6.4
		Operation	2.1	3.7	5.4	14.7
		Power		1.2	1.4	0.6
		TOTAL	5.2	11.0	15.1	28.1
10	60	Amortized capital	1.3	1.9	2.8	3.3
		Maintenance	0.3	0.8	1.6	3.4
		Operation	1.0	1.5	2.3	6.2
		Power		1.1	1.6	0.5
		TOTAL	2.6	5.3	8.3	13.4
10	90	Amortized capital	0.9	1.2	2.2	2.3
		Maintenance	0.2	0.5	1.3	2.6
		Operation	0.5	1.0	1.6	4.2
		Power		1.3	2.8	0.8
		TOTAL	1.6	4.0	7.9	9.9
100	30	Amortized capital	1.4	2.3	1.4	1.4
		Maintenance	0.3	1.2	0.7	1.3
		Operation	1.3	2.2	1.6	3.1
		Power		1.1	0.5	0.4
		TOTAL	3.0	6.8	4.2	6.2
100	60	Amortized capital	0.7	1.0	0.8	0.6
		Maintenance	0.1	0.4	0.4	0.9
		Operation	0.5	0.8	0.7	1.5
		Power		0.9	0.7	0.4
		TOTAL	1.3	3.1	2.6	3.4
100	90	Amortized capital	0.5	0.7	0.6	0.7
		Maintenance	0.1	0.3	0.4	0.8
		Operation	0.3	0.5	0.5	1.1
		Power		1.0	1.2	0.8
		TOTAL	0.9	2.5	2.7	3.4

cost figures to annual costs, this can be accomplished easily by multiplying them by the pounds of oxygen transferred per year, using the pounds per day figures given in Table 6.

It is apparent that the U-tube is a highly attractive aerator for both small and large capacities when the necessary driving force (ΔH) is available. Even if the ΔH must be supplied by pumping, the U-tube is the most economical system at 10 mgd, and for high values of exit dissolved oxygen concentration at 100 mgd.

It is interesting to note that the estimated costs for mechanical aeration are higher than for diffused-air aeration, even though the power performance ratings for diffused air systems are considerably lower. Higher estimated costs for operating and maintaining mechanical aerators are primarily responsible for this. As actual cost data on operating and maintenance expenses for a specific application become available, these cost components can be established with greater certainty.

In Situ Aeration of Sanitary Sewers

Four concepts for in-line aeration of sanitary sewers were selected for economic comparison: (1) an aspirated-air U-tube at the end of a force main, (2) and aspirated-air U-tube in a gravity flow line, (3) a compressed-air U-tube in a force main, and (4) an eductor station. Three of the four types of systems were tested in the Jefferson Parish and Port Arthur projects, mentioned previously.

Table 9 summarizes the principal design and cost bases which were aasumed for all systems. Important characteristics of the individual systems are given in Table 10. The design techniques and procedures were generally similar to those used for the postaeration comparisons. The second case (aspirated-air U-tube in gravity line) required nonstandard use of the U-tube design program, i.e., running multiple cases of type 1 to match the calculated upstream pressure with the ambient pressure.

Cost elements for each of the systems were amortized capital, maintenance, power, and operating labor plus materials. Construction costs were based on actual bid prices received by Jefferson Parish (Ref. 33). A flowrate of 3 mgd was assumed as a basis, and construction bids for smaller systems were adjusted to this capacity, where necessary, using a plant scale factor approach. The construction bid prices were assumed to include contractor's fee, contractor's overhead, and contingency. Fixed capital costs were taken as 110% of the construction bid prices (10% engineering fee).

It should be noted that the construction bid prices are for experimental one-of-a-kind units which include several features which would not be necessary for strictly operational systems. For these reasons (plus the

TABLE 9. SELECTED ECONOMIC AND PHYSICAL DESIGN BASES FOR SEWER *IN SITU* AERATION SYSTEMS

1. Flowrate of 3 mgd (2085 gal/min)
2. Water temperature is 28°C (82.4°F)
3. Ambient pressure is 14.7 lb/sq in. abs.
4. D.O. saturation level is 7.84 mg/liter
5. Incoming waste water has 0.2 mg/liter D.O.
6. α = 0.8
7. General cost bases are identical to those given in Table 5.

TABLE 10. CHARACTERISTICS OF *IN SITU* AERATION SYSTEMS

System	Characteristics				
Eductor station	Construction cost basis is $13,000 for 1,500 gal./min. unit.				
	Casing is 20 ft. deep.				
	Air compressor supplies 40 vol. % air at 59 ft. head.				
	Exit D.O. is 3.3 mg./liter				
Compressed air U-tube in force main	Construction cost bases for 300 gal./min. units are: $11,300 for 20 ft. deep, $11,800 for 30 ft. deep, and $12,800 for 50 ft. deep.				
	Design points are:				
	Depth, ft.	20	30	50	
	Air volume % at 1 atm.	4.5	12	24	
	Exit D.O., mg./liter	2.0	4.0	7.0	
	Extra head on pump, ft.	2.2	4.5	10	
Aspirated air U-tube in force main	Construction cost bases for 1,800 gal./min. units are: $20,300 for 30 ft. deep and $22,700 for 50 ft. deep.				
	Design points have dynamic Δ*H* of 4.0 ft., static Δ*H* of 7.0 ft., and exit D.O. concentrations of 4.2 mg./liter for 30 ft. deep and 5.4 mg./liter for 50 ft. deep.				
Aspirated air U-tube in gravity main	Construction cost bases for 1,800 gal./min. units are identical to those for aspirated-air U-tubes in force mains.				
	Design points are:				
	Depth, ft.	30	30	50	50
	Total Δ*H*, ft.	4	11	4	11
	Exit D.O., mg./liter	2.6	4.6	2.7	5.6

fact that the bids were received during an extremely busy construction period following a major hurricane), the costs are probably much higher than those which should be expected for a straight operational system. In addition there can be large differences in cost due to subsurface soil characteristics and availability of specialized construction equipment; therefore, extreme care should be taken in extrapolation of construction costs to other locations or applications. Although the estimates do not establish generalized absolute costs of the processes, they do give a comparison of relative costs of four types of systems.

A summary of cost estimates for all systems at selected values of exit D.O. is given in Table 11. The differential head column refers to the net increase (or decrease) in system head due to pressure loss (or recovery) through the aerator. Costs are given for two conditions: assuming that the differential head is free or assuming that the additional power costs required to pump the differential head must be paid. The total costs generally range from about 4 to 10 cents per pounds of oxygen added. A general trend for all U-tubes is lower cost at higher differential head, over the range of values investigated.

TABLE 11. COST COMPARISON FOR *IN SITU* AERATION OF SEWER WASTE WATER

				Cost, cents/lb. D.O.				
System	Casing depth, ft.	Exit D.O., mg./liter	Differential head ΔH, ft.	Amortized capital	Maintenance and operating labor	Power	Total	Total including ΔH cost or credit
Eductor station	20	2.2	3.0	3.8	1.9	3.9	10.3	9.6
Compressed air U-tube in force main	20	2.0	2.2	11.0	5.0	0.9	16.1	16.9
	30	4.0	4.5	5.4	2.5	0.9	8.0	8.8
	50	7.0	10.0	3.3	1.5	1.2	5.0	6.0
Aspirated air U-tube in force main	30	4.2	11.0	4.3	0.9	1.8	5.2	7.0
	50	5.4	11.0	3.8	0.7	1.4	4.5	5.9
Aspirated air U-tube in gravity main	30	2.6	4.0	7.3	1.4	1.1	8.7	9.8
	30	4.6	11.0	3.9	0.8	1.7	4.7	6.4
	50	2.7	4.0	7.9	1.5	1.0	9.4	10.4
	50	5.6	11.0	3.6	0.7	1.4	4.3	5.7

It can be seen that the total costs are comparable for three of the systems with similar values of depth and differential head: a compressed air U-tube in a force main, or aspirated-air U-tubes in a force or gravity main. Of these three, an aspirated-air U-tube in a gravity line would present considerably more difficult design and operational problems because of the variations in flowrate and the need to provide differential head within the gravity line. Either of the other two systems would be easier to design and more flexible in operation.

SECTION IX

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SECTION X

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SECTION XII

GLOSSARY

a = air-water interfacial area per unit total volume of water-air mixture

A = area

b = half-angle of venturi conical diffuser

C = concentration of dissolved gas

C_s = saturation concentration of dissolved gas

D = diameter; dissolved oxygen concentration deficit (C_s-C)

E = aspirator contraction area ratio (cross-sectional area of pipe divided by minimum flow cross-sectional area in aspirator)

f* = friction factor for gas lifts (see equation set 10)

F = Change in pressure per unit length (includes both static head and friction losses)

h = step-size, distance along tube for one calculation step

ΔH = differential head

K = overall mass transfer coefficient including interfacial area ($K = K_L a$)

K_L = overall mass transfer coefficient (dimensions are length/time)

L = U-tube depth, measured from top of down-leg to bottom of return bend

M = molecular weight

n = number of moles

n_i = number of moles of "inert" vapors (i.e., air components which are not oxygen or nitrogen)

N = performance rating of aerators (lb oxygen transferred/hp-hr)

p = absolute pressure

p_o = ambient absolute pressure

p_v = vapor pressure of water at prevailing temperature

Q = volumetric flow rate

Q_s = air flow relative to water flow

r = plant production rate

R = ratio of venturi permanent pressure drop to pressure decrease between entrance and the throat: $(p_3 - p_5)/(p_3 - p_4)$

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Re = Reynolds Number

t = time

Δt_a = average time for air bubble to move the distance h

Δt_w = average time for water to move the distance h

T = temperature

u = velocity

u_s = slip velocity = water velocity minus air bubble velocity

u_w = superficial water velocity (i.e., velocity with which the water in an air-water mixture would flow, at the specified volumetric water flow rate, if the air were not present)

V = volume

X = air-water interfacial area per unit volume of air

y = ratio of air volume to liquid volume

y_o = y before mass transfer begins

Greek

α = ratio of mass transfer coefficient for waste water of interest to mass transfer coefficient of "tap water"

μ = viscosity

ρ = density

Subscripts

a = air

d = down-leg of U-tube

m = two-phase mixture of water and air

p = solid particle

s = saturated conditions (e.g., C_s); slip between water and air (for u_s and Q_s)

t = total

T = evaluated at temperature T

u = up-leg of U-tube

w = water

20 = evaluated at a temperature of 20°C (68°F)

Superscripts

o = evaluated at standard conditions (1 atm, 68°F unless otherwise specified)

' = nitrogen, rather than oxygen transfer

$-$ = mean value

SECTION XII

APPENDICES

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APPENDIX A

PILOT-SCALE U-TUBE EXPERIMENTAL DATA

This appendix contains experimental data, plus other quantities calculated with the original data reduction computer program, for the pilot-scale U-tube experimental tests made with a venturi aspirator. Runs 1 through 94 were made with a center-plug aspirator which produced very poor performance. Since this aspirator design was rejected, these data are not given. The information is arranged into three tables, each of which presents results in order of increasing run number. An outline of the contents of the tables and identification of which values are experimental ones are given in the following paragraphs.

Table A-1 contains experimental data for those tests made without air flow (water flow only). The true exit head values include a correction for the curvature and extra length of the outlet hose.

Table A-2 contains measured values of U-tube depth (distance from the entrance of the down-leg to the bottom of the return bend), water flow rate, air-to-water volume percentage (A/W on the print-outs) expressed at 13.8 psia and 68°F (typical conditions at the experimental site), ambient pressure, and water temperature. The amount of oxygen supplied, expressed as mg/l, is equal to 2.63 times the air-to-water volume percentage expressed at 13.8 psia and 68°F. The remaining four columns in Table A-2 contain calculated values of superficial water velocity (the velocity of water in the pipe at the measured volumetric flow rate if no air were present), true overall pressure drop through the system (DELTA H), and values of the mass transfer coefficient K_L, at the water temperature and at 68°F (20°C).

Table A-3 summarizes values of dissolved oxygen concentration, dissolved nitrogen concentration, and head loss relative to the inlet tank water level--with values of each quantity for several stations in the U-tube system. The entrance and exit D.O. concentrations ENTR and EXIT(EXP), are experimental values in all cases. The D.O. concentrations at the exit of the venturi aspirator are experimental values for runs 139-167 and 180-219, inclusive. The D.O. values at the exit of the return bend for runs 225-252 are experimental data. The entries for D.O. concentrations at the platform (i.e., the junction between the straight section of up-leg and the flexible exit hose) are experimental values for runs 273-318. The EXIT (CALC) column gives values of D.O. calculated at the exit of the flexible hose; these were printed primarily as a check (by comparing with the EXIT (EXP) column) that the program had successfully converged. The TRUE EXIT columns for D.O., D.N., and head loss give the calculated values at the exit of a U-tube which has a straight pipe up-leg rather than partly straight pipe plus a flexible

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outlet hose as did the experimental system. The TRUE EXIT HEAD values are identical to the DELTA H values of Table A-2. These true exit values should be used in applying the experimental results to other applications. The values of D.N. are all estimated ones, based on the assumptions discussed in the Data Reduction Program section. The head loss columns for the venturi exit and U-bend entrance contain experimental data exclusively. The column for head loss at U-bend exit contains entirely calculated values. The values for head loss at the platform are experimental data for runs 332-410.

The quantity, weight of oxygen transferred per unit of power expended (N), is a widely used figure-of-merit. However, it can lead to very misleading conclusions if used to compare different types of aeration systems, since power cost is only one component of the total aeration cost. Values of N at standard conditions (tap water at 1 atm, 20° C, and zero inlet D.O.) were calculated for experimental data contained in this appendix and were found to range from less than 1 to nearly 7 lb oxygen/hp-hr. Ranges of N values for each of the five U-tube depths are given below.

U-Tube Depth (ft)	Range of N Values (at standard conditions) from Experimental Data (lb oxygen/hp-hr)
45	1.4 to 5.1
37	1.0 to 6.7
28	0.7 to 6.0
19	1.1 to 4.0
9	0.5 to 1.8

It should be remembered that the ranges of water velocities and air-to-water ratios were not identical for the five U-tube depths; therefore, some differences between the ranges of N for different depths could result from this. In general, the experimental N values seem to increase with increasing U-tube depth, decreasing water velocity and increasing air-to-water ratio. If an aspirated-air U-tube were installed where the required head is available naturally, the value of N would literally be infinite.

TABLE A-1. EXPERIMENTAL DATA FOR U-TUBE TESTS WITH VENTURI ASPIRATOR, NO AIR FLOW

Run Number	U-tube Depth (ft)	Supf. Water Velocity (ft/sec)	Water Flowrate (gpm)	Head Relative to Inlet (ft)		
				Venturi Exit	Bend Entrance	True Exit
95	45.4	2.1	22.1	0.7	1.2	1.8
96	45.4	1.0	10.3	0.2	0.3	0.9
97	45.4	1.9	19.9	0.7	1.0	1.3
98	45.4	2.5	25.8	1.0	1.7	2.2
99	45.4	2.6	27.6	1.3	1.9	2.6
100	45.4	3.0	30.9	1.4	2.3	3.1
101	45.4	3.0	31.9	1.7	2.6	3.5
102	45.4	3.4	35.0	1.8	2.9	4.0
103	45.4	3.5	37.0	2.0	3.2	4.4
104	45.4	3.8	39.3	2.2	3.4	4.8
105	45.4	2.9	30.1	1.4	2.4	3.1
168	18.8	1.8	18.9	0.6	0.7	0.8
169	18.8	2.0	20.6	0.7	0.9	1.0
170	18.8	2.2	22.2	0.9	1.0	1.2
171	18.8	2.4	25.2	1.0	1.3	1.4
172	18.8	2.5	26.5	1.2	1.4	1.6
173	18.8	2.7	28.1	1.3	1.7	1.8
174	18.8	2.8	29.4	1.4	1.8	2.0
175	18.8	3.0	31.2	1.6	1.9	2.2
176	18.8	3.2	33.1	1.7	2.1	2.3
177	18.8	3.4	35.2	1.8	2.2	2.5
178	18.8	3.5	36.2	1.9	2.4	2.7
179	18.8	3.6	37.2	2.0	2.5	2.9
220	8.9	2.7	28.0	1.3	1.4	1.6
221	8.9	2.3	24.2	0.9	1.0	1.2
222	8.9	1.9	20.1	0.7	0.7	0.8
223	8.9	1.4	14.9	0.4	0.4	0.4
224	8.9	3.0	31.4	1.5	1.6	2.1
264	27.9	1.6	16.7	0.5	0.7	0.9
265	27.9	2.0	20.4	0.8	1.0	1.3
266	27.9	1.8	18.8	0.7	0.9	1.1
267	27.9	2.1	21.9	0.9	1.2	1.5
268	27.9	2.3	23.7	1.0	1.3	1.7
269	27.9	2.4	25.3	1.1	1.4	1.9
270	27.9	2.5	25.8	1.2	1.6	2.0
271	27.9	2.8	28.8	1.4	1.9	2.3
272	27.9	3.0	31.8	1.7	2.3	2.8
326	36.5	1.6	16.7	0.5	0.7	0.8
327	36.5	1.9	20.0	0.7	1.0	1.3
328	36.5	2.2	23.0	0.9	1.4	1.8
329	36.5	2.4	25.6	1.0	1.6	2.2
330	36.5	2.7	27.8	1.3	2.0	2.4
331	36.5	3.0	31.2	1.5	2.3	3.0
403	36.5	1.6	16.9	0.5	0.7	0.8
404	36.5	2.0	20.4	0.7	1.0	1.3
405	36.5	2.2	23.3	0.9	1.3	1.7
406	36.5	2.4	25.5	1.0	1.6	2.2
407	36.5	2.7	28.4	1.3	2.0	2.7
408	36.5	2.9	30.3	1.5	2.2	3.1
409	36.5	3.1	32.4	1.7	2.5	3.6
410	36.5	3.4	35.2	1.9	2.7	4.0

TABLE A-2. U-TUBE EXPERIMENTAL DATA WITH CALCULATED MASS TRANSFER COEFFICIENTS

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/W (V/O)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
106	45.42	1.93	20.2	2.10	31.9	71.	2.61	0.935E-03	0.899E-03
107	45.42	2.32	24.3	3.25	31.9	72.	3.67	0.889E-03	0.844E-03
108	45.42	1.91	20.0	4.10	31.9	72.	2.96	0.793E-03	0.752E-03
109	45.42	2.40	25.1	5.50	31.9	72.	4.19	0.788E-03	0.747E-03
110	45.42	1.90	19.9	7.67	31.9	72.	3.41	0.644E-03	0.611E-03
111	45.42	1.90	19.9	8.90	31.9	74.	3.67	0.798E-03	0.738E-03
112	45.42	2.90	30.3	4.36	31.9	75.	6.02	0.106E-02	0.969E-03
113	45.42	2.40	25.1	7.10	31.9	74.	4.73	0.858E-03	0.793E-03
114	45.42	2.90	30.3	2.10	31.9	74.	5.46	0.278E-02	0.256E-02
115	45.42	2.80	29.3	4.82	31.9	75.	5.87	0.135E-02	0.123E-02
116	45.42	1.83	19.1	10.34	31.9	76.	3.54	0.987E-03	0.888E-03
117	45.42	2.40	25.1	6.33	31.8	74.	4.94	0.910E-03	0.841E-03
118	45.42	2.90	30.3	3.27	31.8	75.	5.65	0.144E-02	0.131E-02
119	45.42	2.90	30.3	4.65	31.8	76.	6.11	0.129E-02	0.116E-02
120	45.42	2.41	25.2	3.25	31.8	68.	3.85	0.102E-02	0.102E-02
121	45.42	1.91	20.0	5.35	31.8	70.	3.06	0.846E-03	0.824E-03
122	45.42	2.45	25.6	0.82	31.9	65.	3.54	0.262E-02	0.273E-02
123	45.42	2.41	25.2	2.36	31.9	67.	4.34	0.141E-02	0.143E-02
124	45.42	2.92	30.5	2.90	31.9	68.	5.85	0.130E-02	0.130E-02
125	45.42	2.90	30.3	4.26	31.9	69.	6.19	0.102E-02	0.101E-02
126	45.42	2.32	24.3	7.06	31.9	70.	4.67	0.894E-03	0.870E-03
127	45.42	1.87	19.6	9.57	31.9	70.	3.62	0.760E-03	0.740E-03
128	45.42	1.40	14.6	1.25	31.9	71.	1.35	0.650E-02	0.625E-02
129	45.42	2.86	29.9	1.40	31.9	73.	4.89	0.215E-02	0.201E-02
130	45.42	2.37	24.8	0.84	32.0	73.	3.16	0.280E-02	0.263E-02
131	45.42	2.90	30.3	1.44	32.0	74.	4.92	0.225E-02	0.208E-02
132	45.42	2.41	25.2	4.61	32.0	74.	4.06	0.973E-03	0.899E-03
133	45.42	1.95	20.4	6.60	32.0	76.	3.47	0.902E-03	0.812E-03
134	45.42	1.90	19.9	2.10	31.9	76.	2.49	0.188E-02	0.169E-02
135	45.42	2.83	29.6	3.90	31.9	76.	5.80	0.128E-02	0.115E-02
136	45.42	2.40	25.1	6.70	31.9	75.	5.11	0.100E-02	0.916E-03
137	45.42	2.00	20.9	9.40	31.9	75.	4.15	0.817E-03	0.745E-03
138	45.42	2.83	29.6	4.50	31.9	76.	6.07	0.118E-02	0.106E-02
139	45.42	2.40	25.1	0.90	32.0	75.	3.38	0.314E-02	0.287E-02
140	45.42	2.40	25.1	2.70	32.0	74.	3.67	0.131E-02	0.121E-02
141	45.42	2.40	25.1	5.22	32.0	74.	4.23	0.917E-03	0.847E-03
142	45.42	2.35	24.6	6.49	32.0	75.	4.62	0.892E-03	0.814E-03
143	45.42	2.34	24.5	7.20	32.0	74.	4.87	0.913E-03	0.844E-03
144	45.42	2.94	30.8	3.80	32.0	74.	6.18	0.111E-02	0.103E-02
145	45.42	2.80	29.3	5.20	32.0	74.	6.10	0.111E-02	0.103E-02
147	45.42	2.84	29.7	2.60	31.9	80.	4.90	0.165E-02	0.141E-02
148	45.42	2.90	30.3	3.40	31.9	79.	5.58	0.140E-02	0.121E-02
149	45.42	1.90	19.9	10.10	31.9	78.	3.74	0.771E-03	0.676E-03
150	45.42	1.94	20.3	6.90	31.9	78.	3.60	0.100E-02	0.880E-03
151	45.42	1.86	19.5	3.85	31.9	77.	2.98	0.138E-02	0.122E-02
152	45.42	1.92	20.1	1.70	31.9	75.	2.74	0.932E-02	0.850E-02
153	45.42	1.92	20.1	1.40	31.9	58.	2.46	0.222E-02	0.254E-02
154	45.42	1.86	19.5	2.14	31.9	59.	2.45	0.196E-02	0.220E-02
155	45.42	1.92	20.1	3.60	31.9	60.	2.97	0.124E-02	0.137E-02
156	45.42	1.85	19.4	7.70	31.9	60.	3.33	0.764E-03	0.849E-03
157	45.42	1.87	19.6	9.18	31.9	61.	3.65	0.739E-03	0.810E-03
158	45.42	2.33	24.4	6.20	31.9	62.	4.46	0.901E-03	0.975E-03
159	45.42	2.43	25.4	3.90	31.9	63.	4.13	0.120E-02	0.128E-02
160	45.42	2.33	24.4	2.80	31.9	63.	3.63	0.148E-02	0.158E-02
161	45.42	2.36	24.7	1.30	31.9	63.	3.35	0.312E-02	0.333E-02
162	45.42	2.37	24.8	7.00	31.9	63.	4.83	0.908E-03	0.970E-03
163	45.42	2.88	30.1	3.78	31.9	64.	6.07	0.119E-02	0.126E-02
164	45.42	2.90	30.3	3.80	31.9	64.	6.09	0.132E-02	0.139E-02
165	45.42	2.90	30.3	2.40	31.9	64.	5.49	0.174E-02	0.183E-02

TABLE A-2. (Continued)

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/W (V/D)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
180	18.83	2.34	24.5	1.68	32.0	61.	2.32	0.200E-02	0.220E-02
181	18.83	1.87	19.6	3.63	32.0	63.	1.88	0.147E-02	0.157E-02
182	18.83	1.94	20.3	5.19	32.0	64.	2.15	0.102E-02	0.108E-02
183	18.83	2.31	24.2	2.61	32.0	65.	2.61	0.163E-02	0.170E-02
~~185~~	~~18.83~~	~~2.83~~	~~29.6~~	~~1.76~~	~~32.0~~	~~66.~~	~~3.32~~	~~0.286E-02~~	~~0.294E-02~~
186	18.83	2.44	25.5	4.37	32.0	67.	2.88	0.147E-02	0.149E-02
187	18.83	1.88	19.7	6.82	32.0	67.	2.42	0.126E-02	0.128E-02
188	18.83	2.45	25.6	5.01	32.0	68.	3.22	0.143E-02	0.143E-02
189	18.83	1.91	20.0	8.97	32.0	68.	2.73	0.113E-02	0.113E-02
190	18.83	2.90	30.3	2.02	32.0	68.	4.01	0.279E-02	0.279E-02
~~191~~	~~18.83~~	~~2.85~~	~~29.8~~	~~3.47~~	~~32.0~~	~~68.~~	~~3.99~~	~~0.187E-02~~	~~0.187E-02~~
192	18.83	2.38	24.9	7.02	32.0	69.	3.45	0.144E-02	0.142E-02
193	18.83	1.90	19.9	8.81	32.0	69.	2.64	0.117E-02	0.115E-02
194	18.83	2.37	24.9	7.23	32.0	70.	3.93	0.146E-02	0.142E-02
195	18.83	2.89	30.2	4.11	32.0	69.	4.50	0.189E-02	0.186E-02
196	18.83	2.89	30.2	4.78	32.0	69.	4.83	0.174E-02	0.172E-02
197	18.83	2.30	24.1	7.71	32.0	69.	3.91	~~0.141E-02~~	~~0.140E-02~~
198	18.83	2.34	24.5	8.22	31.9	71.	4.19	0.132E-02	0.127E-02
199	18.83	2.91	30.4	5.58	31.9	70.	5.52	0.123E-02	0.120E-02
200	18.83	2.43	25.4	7.53	31.9	70.	4.49	0.125E-02	0.122E-02
201	18.83	2.80	29.3	6.00	31.9	71.	5.23	0.133E-02	0.129E-02
203	18.83	2.37	24.8	1.09	31.9	70.	2.40	0.547E-02	0.533E-02
~~204~~	~~18.83~~	1.90	19.9	2.71	32.0	62.	1.99	~~0.166E-02~~	~~0.180E-02~~
205	18.83	1.91	20.0	5.44	32.0	63.	2.11	0.926E-03	0.989E-03
206	18.83	1.96	20.3	6.81	32.0	65.	2.39	0.988E-03	0.103E-02
207	18.83	1.92	20.1	8.79	32.0	65.	2.75	0.904E-03	0.941E-03
208	18.83	1.90	19.9	9.98	32.0	66.	3.10	0.860E-03	0.883E-03
209	18.83	2.35	24.6	6.67	32.0	67.	3.57	0.993E-03	0.101E-02
210	18.83	2.41	25.2	6.77	32.0	66.	3.99	0.111E-02	0.114E-02
211	18.83	2.39	25.0	8.60	32.0	67.	4.33	0.109E-02	0.110E-02
212	18.83	2.38	24.9	4.08	32.0	67.	2.78	0.131E-02	0.133E-02
213	18.83	2.37	24.8	1.06	32.0	67.	2.40	0.517E-02	0.524E-02
215	18.83	2.90	30.3	1.42	32.0	67.	3.44	0.322E-02	0.326E-02
216	18.83	2.87	30.0	2.63	32.0	68.	4.08	0.196E-02	0.196E-02
217	18.83	2.90	30.3	4.12	32.0	67.	4.65	0.141E-02	0.143E-02
218	18.83	2.88	30.1	5.11	32.0	68.	5.20	0.124E-02	0.124E-02
219	18.83	2.91	30.4	5.33	32.0	68.	5.44	0.126E-02	0.126E-02
225	8.92	2.35	24.6	2.21	31.8	68.	4.40	0.230E-02	0.230E-02
226	8.92	1.87	19.6	3.15	31.8	69.	3.79	0.233E-02	0.230E-02
227	8.92	1.87	19.6	3.80	31.8	69.	3.86	0.223E-02	0.220E-02
228	8.92	2.44	25.5	2.56	31.8	69.	4.75	0.295E-02	0.295E-02
229	8.92	2.41	25.2	5.51	31.8	68.	5.52	0.176E-02	0.176E-02
230	8.92	1.93	20.2	6.47	31.8	68.	4.35	0.182E-02	0.182E-02
231	8.92	1.94	20.3	9.30	31.8	69.	4.74	0.128E-02	0.127E-02
232	8.92	2.32	24.3	8.03	31.8	69.	5.65	0.146E-02	0.145E-02
233	8.92	2.39	25.0	10.64	31.8	68.	6.83	0.119E-02	0.119E-02
234	8.92	1.86	19.5	20.35	31.8	68.	5.22	0.986E-03	0.986E-03
235	8.92	2.86	29.9	0.63	31.9	65.	4.85	0.360E-02	0.375E-02
236	8.92	2.83	29.6	2.71	31.9	66.	5.39	0.260E-02	0.267E-02
237	8.92	2.84	29.7	4.35	31.9	67.	6.02	0.187E-02	0.190E-02
238	8.92	2.93	30.6	4.71	31.9	68.	6.73	0.123E-02	0.123E-02
239	8.92	2.86	29.9	5.87	31.9	68.	7.13	0.132E-02	0.132E-02
240	8.92	2.88	30.1	6.44	31.9	69.	7.73	0.127E-02	0.125E-02
241	8.92	2.92	30.5	7.16	31.9	69.	8.23	0.133E-02	0.131E-02
242	8.92	2.37	24.8	1.95	31.8	69.	4.41	0.277E-02	0.273E-02
243	8.92	1.90	19.9	3.43	31.8	70.	3.93	0.214E-02	0.209E-02
244	8.92	2.93	30.6	1.27	31.8	70.	5.18	0.363E-02	0.354E-02
245	8.92	2.37	24.8	4.20	31.8	71.	4.61	0.258E-02	0.248E-02
246	8.92	1.90	19.9	5.77	31.8	71.	4.07	0.183E-02	0.176E-02
247	8.92	2.94	30.8	2.63	31.8	72.	5.91	0.223E-02	0.211E-02
248	8.92	2.36	24.7	6.68	31.8	72.	5.71	0.142E-02	0.135E-02
249	8.92	1.87	19.6	8.45	31.8	72.	4.45	0.164E-02	0.156E-02
250	8.92	2.84	29.7	5.04	31.8	73.	6.60	0.181E-02	0.170E-02
251	8.92	2.40	25.1	8.63	31.8	73.	6.53	0.145E-02	0.136E-02
252	8.92	1.96	20.5	13.33	31.8	73.	4.84	0.137E-02	0.129E-02
253	8.92	2.33	24.4	2.16	32.0	68.	4.39	0.208E-02	0.208E-02

TABLE A-2. (Continued)

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/V (V/D)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
254	8.92	1.93	20.2	3.03	32.0	68.	3.96	0.217E-02	0.217E-02
255	8.92	2.43	25.4	5.50	32.0	69.	5.52	0.130E-02	0.128E-02
256	8.92	2.94	29.7	2.29	32.0	70.	5.60	0.245E-02	0.239E-02
257	8.92	1.87	19.6	6.88	32.0	70.	4.16	0.153E-02	0.149E-02
258	8.92	2.43	25.4	9.47	32.0	70.	6.54	0.131E-02	0.127E-02
259	8.92	2.94	29.7	4.88	32.0	70.	6.75	0.190E-02	0.185E-02
260	8.92	1.94	20.3	10.94	32.0	71.	4.94	0.146E-02	0.140E-02
261	8.92	2.35	24.6	10.04	32.0	71.	6.84	0.155E-02	0.149E-02
262	8.92	2.89	30.1	6.05	32.0	71.	7.89	0.163E-02	0.156E-02
263	8.92	1.83	19.7	12.98	32.0	70.	4.58	0.116E-02	0.113E-02
273	27.92	1.88	19.7	4.08	32.0	64.	2.30	0.115E-02	0.121E-02
274	27.92	2.35	24.6	2.15	32.0	64.	2.74	0.140E-02	0.147E-02
275	27.92	2.83	29.6	1.72	32.0	63.	3.74	0.150E-02	0.160E-02
276	27.92	2.36	24.7	2.78	32.0	63.	3.54	0.250E-02	0.268E-02
277	27.92	1.94	20.3	7.10	32.0	64.	2.80	0.809E-03	0.852E-03
278	27.92	1.51	20.0	10.31	32.0	64.	3.22	0.756E-03	0.797E-03
279	27.92	2.36	24.7	6.23	32.0	64.	3.95	0.101E-02	0.106E-02
280	27.92	2.88	30.1	3.21	32.0	64.	4.44	0.134E-02	0.141E-02
281	27.92	2.40	25.1	1.37	31.9	64.	2.94	0.299E-02	0.315E-02
282	27.92	1.88	19.7	3.97	31.9	64.	2.27	0.114E-02	0.120E-02
283	27.92	2.40	25.1	5.57	31.9	65.	3.61	0.930E-03	0.968E-03
284	27.92	2.81	29.4	2.57	31.9	65.	4.24	0.128E-02	0.133E-02
285	27.92	1.91	20.0	9.55	31.9	66.	3.10	0.787E-03	0.808E-03
286	27.92	1.85	19.8	14.42	31.9	67.	3.51	0.709E-03	0.718E-03
287	27.92	2.39	25.0	7.12	31.9	67.	4.60	0.934E-03	0.946E-03
288	27.92	2.87	30.0	4.11	31.9	67.	5.35	0.106E-02	0.107E-02
289	27.92	2.90	30.3	5.37	31.9	67.	6.24	0.103E-02	0.104E-02
290	27.92	2.40	25.1	9.15	31.9	68.	5.66	0.939E-03	0.939E-03
291	27.92	1.92	20.1	14.11	31.9	69.	3.77	0.742E-03	0.742E-03
292	27.92	1.85	19.4	13.59	31.9	68.	4.35	0.905E-03	0.905E-03
293	27.92	1.88	19.7	5.79	31.9	58.	2.45	0.704E-03	0.803E-03
295	27.92	1.88	19.7	1.81	32.0	55.	2.09	0.219E-02	0.260E-02
296	27.92	2.33	24.4	0.89	32.0	57.	2.48	0.326E-02	0.377E-02
297	27.92	2.83	29.6	0.67	32.0	57.	3.32	0.460E-02	0.532E-02
298	27.92	2.41	25.2	2.58	32.0	58.	3.01	0.146E-02	0.167E-02
299	27.92	1.94	20.3	4.61	32.0	58.	2.50	0.117E-02	0.133E-02
300	27.92	1.46	15.3	6.02	32.0	59.	1.95	0.904E-03	0.102E-02
301	27.92	1.90	19.9	8.49	32.0	59.	3.10	0.870E-03	0.980E-03
302	27.92	2.80	29.3	2.53	32.0	60.	4.09	0.166E-02	0.184E-02
303	27.92	3.22	34.7	3.79	32.0	60.	3.80	0.134E-03	0.149E-03
304	27.92	2.35	24.6	6.12	32.0	60.	3.56	0.102E-02	0.113E-02
305	27.92	2.32	24.3	7.19	32.0	61.	4.20	0.106E-02	0.116E-02
306	27.92	1.92	20.1	12.46	32.0	62.	3.36	0.857E-03	0.928E-03
307	27.92	2.92	30.5	3.53	31.9	65.	5.01	0.141E-02	0.146E-02
308	27.92	2.84	29.7	4.73	31.9	65.	5.29	0.118E-02	0.122E-02
309	27.92	2.41	25.2	7.82	31.9	65.	4.97	0.103E-02	0.107E-02
310	27.92	1.91	20.0	16.78	31.9	66.	3.95	0.719E-03	0.739E-03
311	27.92	3.41	35.7	1.40	31.9	67.	5.98	0.401E-02	0.407E-02
312	27.92	2.35	24.6	9.40	31.9	67.	5.19	0.983E-03	0.996E-03
313	27.92	1.91	20.0	15.79	31.9	67.	3.71	0.755E-03	0.765E-03
314	27.92	2.88	30.1	5.85	31.9	67.	6.16	0.129E-02	0.130E-02
315	27.92	2.93	30.6	6.51	31.9	68.	6.86	0.107E-02	0.107E-02
316	27.92	2.40	25.1	10.87	31.9	69.	6.01	0.865E-03	0.865E-03
317	27.92	1.94	20.3	17.83	31.9	69.	4.42	0.656E-03	0.656E-03
318	27.92	3.37	35.2	3.57	31.9	68.	7.36	0.144E-02	0.144E-02
320	27.92	1.46	15.3	2.35	31.7	53.	1.63	0.128E-02	0.156E-02
321	27.92	1.43	15.0	3.64	31.7	53.	1.87	0.824E-03	0.100E-02
322	27.92	1.44	15.1	5.68	31.7	54.	1.89	0.633E-03	0.762E-03
323	27.92	1.42	14.9	7.77	31.7	54.	2.00	0.505E-03	0.608E-03
325	27.92	3.40	35.6	4.03	31.7	55.	7.43	0.719E-03	0.853E-03

TABLE A-2. (Concluded)

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/W (V/O)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
332	36.50	1.89	19.8	2.71	32.0	66.	2.55	0.324E-02	0.332E-02
333	36.50	1.44	15.1	3.61	32.0	67.	2.15	0.287E-02	0.290E-02
335	36.50	2.80	29.3	0.82	32.0	69.	4.05	0.237E-01	[illegible]
336	36.50	2.41	25.2	2.78	32.0	69.	3.59	0.201E-02	0.198E-02
337	36.50	1.89	19.7	5.78	32.0	70.	2.89	0.226E-02	0.220E-02
338	36.50	1.46	15.3	5.83	32.0	71.	2.32	0.488E-02	0.469E-02
339	36.50	1.87	19.6	9.11	32.0	71.	3.32	0.210E-02	0.202E-02
340	36.50	1.45	15.2	10.39	32.0	72.	2.82	0.127E-02	0.120E-02
341	36.50	2.41	25.2	5.66	32.0	72.	4.16	0.158E-02	0.150E-02
342	36.50	2.87	30.0	3.22	32.0	71.	4.71	0.194E-02	0.186E-02
344	36.50	1.89	19.8	10.77	31.9	74.	4.23	0.103E-02	0.955E-03
345	36.50	2.41	25.2	6.36	31.9	74.	5.44	0.121E-02	0.112E-02
346	36.50	2.83	29.6	3.94	31.9	75.	5.87	0.131E-02	0.120E-02
347	36.50	2.85	29.8	4.51	31.9	75.	6.17	0.112E-02	0.102E-02
348	36.50	2.41	25.2	6.36	31.9	76.	5.79	0.150E-02	0.135E-02
349	36.50	1.91	20.0	14.20	31.9	76.	4.41	0.930E-03	0.837E-03
350	36.50	1.87	19.6	15.79	31.9	76.	4.27	0.893E-03	0.804E-03
356	36.50	1.46	15.3	5.13	31.9	70.	2.84	0.150E-02	0.146E-02
357	36.50	1.41	14.7	7.06	31.9	71.	2.80	0.438E-03	0.421E-03
358	36.50	1.38	14.4	4.98	31.9	71.	2.69	0.277E-02	0.266E-02
359	36.50	1.45	15.6	11.12	31.9	71.	2.72	0.974E-03	0.937E-03
360	36.50	1.45	15.2	11.97	31.9	72.	3.09	0.910E-03	0.863E-03
361	36.50	1.42	14.9	8.40	31.9	72.	3.24	0.110E-02	0.104E-02
362	36.50	1.51	20.0	1.49	31.9	73.	2.88	0.610E-02	0.571E-02
363	36.50	1.92	20.1	2.65	31.9	73.	3.12	0.210E-02	0.197E-02
364	36.50	1.90	19.9	3.86	31.9	73.	3.24	0.154E-02	0.144E-02
365	36.50	1.51	20.0	5.70	31.9	73.	3.47	0.120E-02	0.112E-02
366	36.50	1.50	19.9	7.25	31.9	73.	3.80	0.110E-02	0.103E-02
367	36.50	1.50	19.9	8.53	31.9	73.	3.99	0.111E-02	0.103E-02
368	36.50	1.93	20.2	10.29	31.9	74.	4.18	0.104E-02	0.964E-03
369	36.50	1.88	19.7	12.59	31.9	75.	4.33	0.983E-03	0.896E-03
370	36.50	1.90	19.9	11.73	31.9	75.	3.92	0.941E-03	0.858E-03
371	36.50	1.94	20.3	12.99	31.9	76.	4.21	0.101E-02	0.908E-03
372	36.50	1.86	19.5	11.90	31.9	77.	4.34	0.117E-02	0.104E-02
373	36.50	1.86	19.5	13.12	31.9	77.	3.78	0.971E-03	0.863E-03
374	36.50	1.93	20.2	13.50	31.9	78.	4.32	0.951E-03	0.834E-03
375	36.50	1.43	15.0	7.00	33.0	68.	1.82	0.510E-03	0.510E-03
377	36.50	2.41	25.2	1.96	33.0	70.	3.40	0.522E-02	0.508E-02
378	36.50	2.35	24.6	3.18	33.0	70.	3.48	0.222E-02	0.216E-02
379	36.50	2.39	25.0	5.07	33.0	70.	3.72	0.154E-02	0.150E-02
380	36.50	2.41	25.2	5.94	33.0	70.	4.09	0.145E-02	0.141E-02
381	36.50	2.39	25.0	6.42	33.0	71.	4.44	0.139E-02	0.134E-02
382	36.50	2.39	25.0	6.59	33.0	71.	4.75	0.137E-02	0.132E-02
383	36.50	2.35	24.6	7.55	33.0	71.	4.98	0.134E-02	0.129E-02
384	36.50	2.38	24.9	8.29	33.0	71.	5.28	0.133E-02	0.128E-02
385	36.50	2.38	24.9	9.03	33.0	72.	5.62	0.129E-02	0.122E-02
386	36.50	2.39	25.0	10.02	33.0	72.	6.08	0.119E-02	0.113E-02
388	36.50	2.87	30.0	0.78	31.8	73.	4.17	0.535E-02	0.501E-02
389	36.50	2.81	29.4	1.65	31.8	73.	4.30	0.249E-02	0.234E-02
390	36.50	2.88	30.1	2.37	31.8	74.	4.86	0.172E-02	0.159E-02
391	36.50	2.85	29.8	3.22	31.8	74.	5.18	0.142E-02	0.131E-02
392	36.50	2.83	29.6	3.88	31.8	74.	5.49	0.132E-02	0.122E-02
393	36.50	2.81	29.4	4.25	31.8	75.	5.70	0.129E-02	0.118E-02
394	36.50	2.85	29.8	4.66	31.8	75.	6.06	0.132E-02	0.120E-02
395	36.50	2.88	30.1	5.26	31.8	75.	5.44	0.131E-02	0.120E-02
396	36.50	2.92	30.5	5.65	31.8	75.	5.95	0.127E-02	0.115E-02
397	36.50	3.32	34.7	3.45	31.8	75.	7.50	0.159E-02	0.145E-02
398	36.50	3.23	33.8	2.92	31.8	75.	6.63	0.168E-02	0.153E-02
400	36.50	3.31	34.6	1.70	31.7	54.	5.70	0.149E-02	0.180E-02
401	36.50	3.32	34.7	3.00	31.7	54.	6.51	0.118E-02	0.142E-02
402	36.50	3.27	35.2	3.91	31.7	55.	7.52	0.121E-02	0.144E-02

TABLE A-3. U-TUBE EXPERIMENTAL DATA WITH CALCULATED GAS CONCENTRATIONS AND HEAD LOSSES AT OTHER STATIONS

RUN NO.	D.O. CONCENTRATIONS (MG/L) ENTR	VENTURI EXIT	BEND EXIT	PLATE	EXIT (CALC)	EXIT (EXP)	TRUE EXIT	D.N. CONC. (MG/L) ENTR	BEND EXIT	TRUE EXIT	HEAD RELATIVE TO INLET (FEET) VENTURI EXIT	BEND ENTR	BEND EXIT	PLATE	EXIT (EXP)	TRUE EXIT
106	1.65	1.79	3.09	3.69	3.87	3.87	3.80	3.30	7.15	9.27	0.90	2.30	2.37	2.60	2.70	2.41
107	1.63	1.93	3.44	4.20	4.41	4.41,	4.31	3.26	8.15	10.59	1.65	3.30	3.41	3.68	3.75	3.67
108	1.63	1.90	3.95	4.90	5.14	5.14	5.04	3.26	9.63	12.52	1.10	3.10	3.17	3.07	3.75	2.96
109	1.55	2.09	4.18	5.22	5.47	5.47	5.35	3.10	10.12	13.13	2.00	4.25	4.37	4.31	5.00	4.19
110	1.63	2.13	5.01	6.29	6.53	6.53	6.42	3.26	12.31	15.31	1.00	4.30	4.37	3.71	4.75	3.41
111	1.52	2.09	5.80	7.24	7.36	7.36	7.30	3.04	12.53	15.49	1.70	4.80	4.87	4.02	5.75	3.67
112	1.43	1.99	3.73	4.61	4.83	4.83	4.69	2.86	8.33	10.98	3.30	5.35	5.53	6.01	6.25	6.02
113	1.36	2.04	4.70	5.94	6.16	6.16	6.04	2.72	10.71	13.78	2.70	5.10	5.22	4.91	6.00	4.73
114	1.28	1.57	3.52	4.21	4.32	4.32	4.25	2.56	5.76	7.57	2.80	4.30	4.48	5.34	5.25	5.46
115	1.43	2.01	4.37	5.43	5.62	5.62	5.50	2.86	8.79	11.58	3.30	5.40	5.57	5.89	6.40	5.87
116	1.49	2.12	6.91	8.36	8.23	8.23	8.27	2.98	12.92	15.76	1.50	5.00	5.07	3.97	5.80	3.54
117	1.60	2.18	4.69	5.86	6.07	6.07	5.95	3.20	10.51	13.47	2.80	5.15	5.27	5.08	5.75	4.94
118	1.50	1.92	3.66	4.48	4.67	4.67	4.56	3.00	7.41	9.77	3.00	4.75	4.93	5.59	5.75	5.65
119	1.41	2.01	4.13	5.12	5.32	5.32	5.19	2.82	8.51	11.21	3.30	5.50	5.68	6.11	6.50	6.11
120	1.61	1.93	3.63	4.45	4.67	4.67	4.57	3.22	8.20	10.82	1.80	3.40	3.52	3.84	4.00	3.85
121	2.32	2.62	5.10	6.19	6.39	6.39	6.30	4.64	11.53	14.39	1.30	3.40	3.47	3.22	4.25	3.06
122	1.94	2.02	2.57	3.28	3.35	3.35	3.32	3.88	5.39	6.38	1.50	2.50	2.62	3.38	3.50	3.54
123	1.90	2.12	3.76	4.48	4.65	4.65	4.55	3.80	7.60	9.77	1.75	3.70	3.82	4.29	4.00	4.34
124	1.79	2.16	3.67	4.42	4.61	4.61	4.49	3.58	7.69	9.97	2.90	4.85	5.03	6.77	5.75	5.85
125	1.69	2.21	3.95	4.44	5.06	5.06	4.92	3.38	8.86	11.56	3.50	5.50	5.68	6.17	6.40	6.19
126	1.67	2.28	5.19	6.47	6.68	6.68	6.57	3.34	11.43	14.53	2.40	5.10	5.21	4.86	5.60	4.67
127	1.92	2.49	6.35	7.84	7.93	7.93	7.88	3.85	13.56	16.43	1.70	4.90	4.97	4.01	5.70	3.62
128	1.74	1.79	4.13	4.13	4.02	4.14	4.00	3.48	6.69	8.43	0.40	1.20	1.23	1.35	2.00	1.35
129	1.46	1.65	2.79	3.28	3.40	3.40	3.33	2.92	5.16	6.55	2.20	3.60	3.77	4.73	4.75	4.89
130	1.54	1.62	2.62	2.93	3.00	3.00	2.97	3.08	4.61	5.50	1.30	2.20	2.31	3.01	3.00	3.16
131	1.44	1.64	2.83	3.33	3.45	3.45	3.38	2.88	5.15	6.56	2.25	3.60	3.78	4.76	4.75	4.92
132	1.92	2.34	4.35	5.32	5.53	5.53	5.43	3.84	9.70	12.45	2.00	3.90	4.02	4.12	4.75	4.06
133	2.20	2.60	5.56	6.78	6.92	6.92	6.85	4.40	11.98	14.74	1.60	4.10	4.17	3.70	4.50	3.47
134	1.72	1.86	3.91	4.59	4.70	4.70	4.66	3.44	7.18	9.28	0.80	2.20	2.27	2.48	2.75	2.49
135	1.41	1.88	3.76	4.65	4.86	4.86	4.73	2.82	7.86	10.43	4.20	5.10	5.27	5.77	6.00	5.80
136	1.74	2.34	5.11	6.32	6.49	6.49	6.39	3.48	10.84	13.74	2.80	5.40	5.52	5.26	6.00	5.11
137	1.66	2.29	5.92	7.34	7.44	7.44	7.39	3.32	12.53	15.37	2.20	5.30	5.38	4.49	5.80	4.15
138	1.88	2.39	4.20	5.22	5.41	5.41	5.29	3.76	9.06	11.60	3.40	5.50	5.67	6.07	6.25	6.07
139	1.51	1.60	2.71	3.04	3.10	3.10	3.07	3.02	4.62	5.66	1.40	2.40	2.52	3.25	3.30	3.38
140	1.53	1.80	3.47	4.23	4.42	4.42	4.33	3.06	7.22	9.53	1.50	3.10	3.22	3.63	4.00	3.67
141	1.45	1.96	4.17	5.22	5.46	5.46	5.34	2.90	9.59	12.57	2.10	4.20	4.32	4.32	5.00	4.23
142	1.59	2.18	4.73	5.91	6.12	6.12	6.01	3.18	10.63	13.61	2.50	4.90	5.02	4.77	5.70	4.62
143	1.53	2.17	5.04	6.30	6.50	6.50	6.39	3.06	11.03	14.36	2.80	5.30	5.42	5.05	5.75	4.97
144	1.45	1.95	3.55	4.37	4.58	4.58	4.45	2.90	7.87	10.39	3.50	5.35	5.54	6.14	6.25	6.19
145	1.37	2.01	4.19	5.24	5.46	5.46	5.32	2.74	9.06	11.93	3.40	5.70	5.87	6.13	6.30	6.10
147	1.66	1.99	3.52	4.22	4.38	4.38	4.29	3.32	6.85	8.84	2.35	3.90	4.07	4.81	5.00	4.90
148	1.75	2.18	3.83	4.62	4.80	4.80	4.69	3.50	7.79	10.04	2.90	4.70	4.88	5.52	5.80	5.58
149	2.16	2.73	6.30	7.66	7.70	7.70	7.68	4.32	13.16	15.65	2.00	5.10	5.17	4.15	5.50	3.74
150	2.16	2.58	5.84	7.08	7.16	7.16	7.12	4.32	11.98	14.70	1.70	4.30	4.37	3.85	4.70	3.60
151	1.95	2.18	4.96	5.95	6.07	6.07	6.02	3.90	9.67	12.38	1.30	3.10	3.16	3.08	4.00	2.98
152	2.06	2.17	5.14	5.07	4.83	5.08	4.84	4.12	7.24	9.10	1.00	2.35	2.42	2.71	2.80	2.74
153	2.57	2.66	4.40	4.88	4.95	4.95	4.92	5.14	8.04	9.79	0.80	2.00	2.07	2.41	2.25	2.46
154	2.64	2.76	5.17	5.85	5.93	5.93	5.90	5.28	9.45	11.78	0.90	2.20	2.26	2.45	2.80	2.45
155	2.70	2.91	5.62	6.64	6.80	6.80	6.73	5.40	11.33	14.22	1.30	3.00	3.07	3.05	3.60	2.97
156	2.79	3.19	6.78	8.23	8.38	8.38	8.31	5.58	14.81	17.83	1.50	4.25	4.32	3.63	4.75	3.33
157	2.58	3.08	7.00	8.54	8.65	8.65	8.60	5.16	15.01	17.96	1.75	4.85	4.92	4.02	5.10	3.65
158	2.37	2.87	5.63	6.89	7.10	7.10	6.99	4.74	12.33	15.46	2.35	4.70	4.81	4.60	5.20	4.46
159	2.28	2.63	4.89	5.90	6.10	6.10	6.00	4.56	10.13	12.95	2.00	3.80	3.92	4.15	4.40	4.13
160	2.25	2.49	4.56	5.41	5.58	5.58	5.50	4.50	8.96	11.44	1.70	3.15	3.26	3.61	3.70	3.63
161	2.25	2.37	4.02	4.45	4.50	4.50	4.48	4.50	6.84	8.33	1.40	2.50	2.61	3.23	3.00	3.35
162	2.34	2.91	5.97	7.19	7.38	7.38	7.28	4.68	12.64	15.72	2.50	5.20	5.32	5.00	5.80	4.83
163	2.14	2.57	4.41	5.31	5.52	5.52	5.39	4.28	9.31	11.92	3.40	5.30	5.48	6.03	6.25	6.07
164	2.14	2.58	4.56	5.50	5.70	5.70	5.57	4.28	9.32	11.94	3.50	5.30	5.48	6.05	6.30	6.09
165	2.05	2.34	4.00	4.74	4.90	4.90	4.80	4.10	7.68	9.78	2.80	4.40	4.58	5.39	5.60	5.49

TABLE A-3. (Continued)

	D.O. CONCENTRATIONS (MG/L)							D.N. CONC.(MG/L)			HEAD RELATIVE TO INLET (FEET)					
RUN NO.	ENTR	VENTURI EXIT	BEND EXIT	PLATE	EXIT (CALC)	EXIT (EXP)	TRUE EXIT	D.N. ENTR	BEND EXIT	TRUE EXIT	VENTURI EXIT	BEND ENTR	BEND EXIT	PLATE	EXIT (EXP)	TRUE EXIT
180	1.94	2.09	2.87	3.12	3.50	3.50	3.37	3.88	6.29	8.01	1.40	2.00	2.11	2.22	2.50	2.32
181	1.89	2.12	3.57	4.03	4.69	4.69	4.49	3.78	8.92	11.76	1.15	1.95	2.02	1.98	2.50	1.88
182	2.14	2.47	3.82	4.25	4.91	4.91	4.69	4.28	10.41	13.30	1.35	2.35	2.42	2.33	2.70	2.15
183	2.39	2.59	3.60	3.73	4.23	4.23	4.06	4.76	7.93	10.01	1.80	2.40	2.51	2.57	3.00	2.61
185	2.27	2.67	3.28	3.54	3.92	3.92	3.77	4.54	6.59	9.06	2.20	2.80	2.97	3.15	3.50	3.32
186	2.41	2.79	3.98	4.34	4.91	4.91	4.69	4.82	9.27	11.78	1.80	2.80	2.93	2.93	3.30	2.88
187	2.41	2.79	4.70	5.27	6.03	6.03	5.78	4.82	11.65	14.31	1.60	2.80	2.87	2.70	3.20	2.42
188	2.30	2.76	4.01	4.42	5.03	5.03	4.78	4.60	9.54	12.12	1.15	3.20	3.33	3.30	3.60	3.22
189	2.30	2.82	4.89	5.51	6.31	6.31	6.03	4.60	12.39	14.83	1.80	3.30	3.38	3.12	4.00	2.73
190	2.13	2.37	3.24	3.51	3.92	3.92	3.73	4.26	6.52	8.11	2.65	3.50	3.68	3.85	3.80	4.01
191	2.22	2.61	3.50	3.93	4.44	4.44	4.20	4.44	7.94	10.12	2.80	3.65	3.83	3.93	4.20	3.99
192	2.78	2.86	4.51	5.03	5.74	5.74	5.45	4.56	10.62	13.30	2.50	3.65	3.78	3.65	4.50	3.45
193	2.36	2.86	4.33	5.55	6.33	6.33	6.06	4.72	12.31	14.72	1.80	3.20	3.27	3.02	3.65	2.64
194	2.25	2.73	4.52	5.05	5.76	5.76	5.44	4.50	10.59	13.22	2.85	4.15	4.27	4.13	4.80	3.93
195	2.11	2.59	3.71	4.03	4.64	4.64	4.36	4.22	8.17	10.51	3.30	4.20	4.39	4.46	5.00	4.50
196	2.11	2.65	3.83	4.22	4.91	4.81	4.50	4.22	8.61	11.06	3.60	4.60	4.79	4.93	5.25	4.83
197	2.19	2.79	4.60	5.16	5.91	5.91	5.58	4.38	10.90	13.57	2.90	4.20	4.32	4.15	5.25	3.91
198	1.81	2.50	4.24	4.94	5.69	5.69	5.25	3.62	10.54	13.26	3.00	4.50	4.62	4.43	5.50	4.19
199	1.67	2.36	3.34	3.69	4.25	4.25	3.93	3.34	8.43	11.08	4.25	5.35	5.54	5.55	6.20	5.52
200	2.08	2.72	4.22	4.71	5.41	5.41	5.07	4.16	10.41	13.07	3.35	4.70	4.83	4.68	5.80	4.49
201	2.06	2.69	3.91	4.20	4.78	4.78	4.46	4.17	9.18	11.72	4.00	5.15	5.33	5.30	6.20	5.23
203	2.17	2.27	3.24	3.67	3.75	3.75	3.67	4.34	5.73	6.90	1.40	2.00	2.11	2.25	2.50	2.40
204	1.92	2.09	3.35	3.72	4.29	4.29	4.11	3.94	7.94	10.44	1.20	1.95	2.02	2.02	2.25	1.99
205	1.99	2.33	3.68	4.11	4.79	4.79	4.56	3.98	10.55	13.55	1.40	2.35	2.42	2.31	2.75	2.11
206	1.83	2.27	3.92	4.44	5.21	5.21	4.94	3.66	11.08	14.07	1.70	2.75	2.83	2.66	3.25	2.39
207	1.83	2.38	4.24	4.92	5.65	5.65	5.35	3.66	12.13	14.90	1.90	3.30	3.38	3.13	3.80	2.75
208	1.74	2.35	4.30	4.90	5.76	5.76	5.43	3.48	12.44	15.03	2.20	3.75	3.83	3.52	3.90	3.10
209	1.81	2.39	3.65	4.03	4.75	4.75	4.46	3.62	10.97	12.98	2.60	3.75	3.87	3.75	4.50	3.57
210	1.83	2.44	3.92	4.28	4.93	4.94	4.66	3.66	10.10	13.04	3.00	4.15	4.28	4.16	5.00	3.99
211	1.64	2.40	4.04	4.57	5.35	5.35	4.98	3.28	10.74	13.65	3.20	4.65	4.78	4.58	5.50	4.33
212	1.73	2.11	3.21	3.57	4.14	4.14	3.92	3.46	8.19	10.80	1.75	2.70	2.82	2.92	3.50	2.79
213	1.55	1.65	2.66	2.89	3.19	3.19	3.11	3.10	4.67	5.97	1.50	2.00	2.11	2.25	2.50	2.40
215	1.47	1.66	2.63	2.66	3.02	3.02	2.87	2.94	4.79	6.13	2.20	2.85	3.03	3.23	3.50	3.44
216	1.45	1.79	2.67	2.96	3.42	3.42	3.20	2.90	6.02	8.08	2.85	3.65	3.83	3.97	4.25	4.08
217	1.55	2.07	3.02	3.35	3.88	3.88	3.61	3.10	7.47	10.03	3.40	4.35	4.54	4.61	5.25	4.65
[illegible]	1.45	2.09	3.09	3.44	4.01	4.01	3.70	2.90	7.99	10.75	4.00	5.00	5.19	5.21	5.60	5.20
219	1.45	2.11	3.16	3.52	4.10	4.10	3.77	2.90	8.10	10.88	4.25	5.25	5.44	5.46	6.10	5.44
225	1.02	1.93	2.31	2.31	2.98	2.99	2.66	3.24	4.96	6.82	1.70	1.90	2.01	4.34	2.50	4.40
226	1.94	2.13	2.95	2.93	3.36	3.96	3.55	3.98	6.37	8.00	1.10	1.45	1.52	3.85	2.50	3.79
227	1.68	1.92	2.88	2.89	4.06	4.06	3.57	3.36	6.37	9.20	1.20	1.55	1.62	3.95	3.00	3.86
228	1.62	1.87	2.53	2.53	3.40	3.40	2.98	3.24	5.16	7.19	1.90	2.25	2.37	4.70	3.00	4.75
229	1.70	2.21	2.99	2.99	4.08	4.08	3.48	3.40	6.96	9.94	2.70	3.15	3.28	5.61	4.00	5.52
230	1.70	2.12	3.31	3.31	4.77	4.77	4.13	3.40	7.73	11.31	1.65	2.15	2.23	4.56	4.00	4.35
231	1.77	2.36	3.46	3.46	4.88	4.88	4.19	3.54	8.75	12.41	1.90	2.65	2.73	5.06	5.00	4.74
232	1.60	2.29	3.20	3.20	4.46	4.46	3.76	3.20	7.73	11.24	2.80	3.40	3.52	5.95	5.00	5.65
233	1.53	2.45	3.34	3.34	4.60	4.60	3.78	3.06	8.31	11.95	3.80	4.60	4.74	7.07	6.00	6.83
234	1.70	2.84	4.29	4.29	6.04	6.04	5.18	3.40	10.63	13.97	2.20	3.50	3.59	5.92	6.00	5.22
235	1.67	1.75	1.94	1.94	2.20	2.20	2.07	3.34	3.85	4.42	1.90	2.15	2.32	4.65	3.00	4.85
236	1.57	1.91	2.45	2.45	3.22	3.22	2.80	3.14	5.10	7.07	2.50	2.80	2.98	5.31	3.75	5.39
237	1.55	2.09	2.67	2.67	3.53	3.53	3.01	3.10	5.95	8.56	3.10	3.50	3.68	6.01	4.50	6.02
238	1.53	2.13	2.52	2.52	3.15	3.15	2.73	3.06	6.02	9.64	3.75	4.20	4.40	6.73	5.00	6.73
239	1.45	2.16	2.69	2.69	3.49	3.49	2.94	2.90	6.43	9.40	4.10	4.65	4.84	7.17	5.75	7.13
240	1.43	2.29	2.72	2.72	3.54	3.54	2.94	2.86	6.56	9.58	4.75	5.25	5.45	7.78	6.50	7.73
241	1.35	2.22	2.80	2.80	3.70	3.70	3.01	2.70	6.69	9.83	5.15	5.75	5.96	8.29	7.25	8.23
242	1.63	1.87	2.36	2.36	3.03	3.03	2.72	3.36	4.87	6.53	1.65	1.90	2.02	4.35	2.50	4.41
243	1.66	1.88	2.71	2.71	3.74	3.74	3.30	3.32	[illegible]	8.77	1.25	1.60	1.67	4.00	2.50	3.93
244	1.41	1.59	1.93	1.93	2.41	2.41	2.16	2.82	3.39	4.34	2.20	2.50	2.68	5.01	3.30	5.18
245	1.40	1.81	2.72	2.72	3.89	3.89	3.34	2.80	5.76	8.56	1.80	2.20	2.32	4.65	3.50	4.61
246	1.40	1.79	2.90	2.90	4.28	4.28	3.70	2.80	6.94	10.47	1.35	1.85	1.92	4.25	3.50	4.07
247	1.39	1.75	2.16	2.16	2.77	2.77	2.41	2.78	4.63	6.43	3.00	3.30	3.49	5.82	4.25	5.91
248	1.39	2.00	2.76	2.76	3.83	3.83	3.22	2.78	6.82	10.14	2.90	3.40	3.53	5.86	4.50	5.71
249	1.39	1.93	3.28	3.28	4.89	4.89	4.18	2.78	9.01	11.90	1.70	2.35	2.42	4.75	4.50	4.45
250	1.37	1.99	2.59	2.59	3.47	3.47	2.90	2.74	5.85	8.53	3.70	4.10	4.29	6.62	5.25	6.60
251	1.37	2.16	3.04	3.04	4.27	4.27	3.50	2.74	7.37	10.83	3.65	4.25	4.39	6.72	5.50	6.53
252	1.37	2.26	3.69	3.63	5.40	5.40	4.61	2.74	9.06	12.75	2.20	2.90	2.99	5.32	5.50	4.84
253	1.45	1.66	2.10	2.10	2.73	2.73	2.43	2.90	4.65	6.53	1.55	1.90	2.01	4.36	2.50	4.39
254	1.45	1.66	2.44	2.44	3.42	3.42	3.00	2.90	5.48	8.12	1.20	1.60	1.67	4.00	2.50	3.96
255	1.56	2.09	2.68	2.68	3.55	3.55	3.05	3.12	6.63	9.72	2.70	3.15	3.28	5.61	4.00	5.52
256	1.42	1.72	2.14	2.14	2.76	2.76	2.41	2.84	4.52	6.22	2.75	3.00	3.18	5.51	3.75	5.60
257	1.59	2.02	3.12	3.12	4.51	4.51	3.90	3.18	7.77	11.42	1.50	2.00	2.07	4.40	4.00	4.16
258	1.42	2.21	3.02	3.02	4.18	4.19	3.45	2.84	7.49	11.03	3.65	4.25	4.39	6.72	5.50	6.54
259	1.34	1.95	2.59	2.59	3.51	3.51	2.91	2.68	5.80	9.55	3.75	4.25	4.43	6.76	5.00	6.75
260	1.41	2.13	3.53	3.53	5.21	5.21	4.41	2.82	8.71	12.55	2.20	2.90	2.99	5.32	5.50	4.94
261	1.41	2.28	3.36	3.35	4.80	4.80	3.88	2.82	7.94	11.56	3.80	4.60	4.73	7.06	7.00	6.84
262	1.24	1.99	2.62	2.62	3.56	3.55	2.87	2.48	6.08	7.07	4.90	5.40	5.60	7.93	6.75	7.89
263	1.50	2.31	3.63	3.63	5.27	5.27	4.52	3.00	9.45	13.21	1.75	2.65	2.73	5.06	7.00	4.58

TABLE A-3. (Continued)

RUN NO.	D.O. CONCENTRATIONS (MG/L)							D.N. CONC.(MG/L)			HEAD RELATIVE TO INLET (FEET)					
	ENTR	VENTURI EXIT	BEND EXIT	PLATE	EXIT (CALC)	EXIT (EXP)	TRUE EXIT	ENTR	BEND EXIT	TRUE EXIT	VENTURI EXIT	BEND ENTR	BEND EXIT	PLATE	EXIT (EXP)	TRUE EXIT
273	1.98	2.14	4.05	4.81	5.27	5.27	5.11	3.76	10.44	13.41	1.15	2.45	2.52	2.42	3.00	2.30
274	1.88	2.09	3.10	3.54	3.84	3.84	3.72	3.76	7.32	9.45	1.50	2.35	2.46	2.67	3.00	2.74
275	1.81	2.01	2.76	3.10	3.34	3.34	3.21	3.62	6.30	8.02	2.20	3.00	3.17	3.59	4.00	3.74
276	1.81	2.07	4.10	4.79	5.15	5.15	5.00	3.62	8.99	10.65	1.65	3.25	3.36	3.51	4.00	3.54
277	1.96	2.41	4.55	5.46	5.58	5.58	5.71	3.92	12.99	15.72	1.65	3.35	3.42	3.08	4.00	2.80
278	1.96	2.59	5.26	6.34	6.88	6.98	6.66	3.92	14.67	16.74	1.80	4.20	4.28	3.66	5.00	3.22
279	1.98	2.43	4.32	5.14	5.63	5.63	5.40	3.76	11.40	14.35	2.40	4.15	4.27	4.10	5.00	3.95
280	1.79	2.19	3.32	3.85	4.20	4.20	4.02	3.58	8.00	10.47	2.85	3.90	4.08	4.36	5.00	4.44
281	2.40	2.52	3.66	4.06	4.27	4.27	4.19	4.80	7.05	8.55	1.35	2.40	2.52	2.91	3.00	2.94
282	2.49	2.72	4.48	5.15	5.61	5.61	5.46	4.98	11.10	13.80	1.25	2.40	2.47	2.38	3.00	2.27
283	2.38	2.85	4.35	5.04	5.46	5.46	5.27	4.76	11.36	14.09	2.15	3.70	3.82	3.73	4.50	3.61
284	2.29	2.58	3.45	3.96	4.14	4.14	4.00	4.56	8.06	10.12	2.50	3.65	3.82	4.14	4.50	4.24
285	2.44	2.92	5.19	6.13	6.61	6.61	6.42	4.98	14.08	16.21	1.70	3.85	3.92	3.45	4.50	3.10
286	2.49	3.26	6.13	7.24	7.65	7.65	7.47	4.98	15.71	16.75	1.65	5.00	5.08	4.13	6.00	3.51
287	2.24	2.82	4.60	5.40	5.65	5.85	5.62	4.48	11.99	14.57	3.15	4.90	5.02	4.78	6.00	4.50
288	1.58	2.45	3.53	4.04	4.39	4.39	4.19	3.96	8.96	11.49	1.65	4.95	5.13	5.32	6.00	5.35
289	1.98	2.63	3.91	4.51	4.90	4.90	4.66	3.96	9.98	12.59	2.60	6.00	6.19	6.26	7.50	6.24
290	2.18	2.91	5.00	5.90	6.35	6.35	6.09	4.36	12.70	14.98	3.60	6.20	6.33	5.90	7.50	5.66
291	2.44	3.21	6.07	7.17	7.57	7.57	7.39	4.98	15.41	16.51	2.00	5.20	5.28	4.35	7.50	3.77
292	2.52	3.44	7.31	9.50	8.61	9.61	8.55	5.04	15.93	16.52	2.20	6.30	6.38	5.08	9.25	4.35
293	2.85	3.17	4.86	5.62	6.08	6.09	5.91	5.70	13.67	16.34	1.30	2.85	2.92	2.67	3.50	2.45
295	2.39	2.50	4.14	4.67	4.96	4.96	4.87	4.78	8.55	10.75	0.95	1.90	1.96	2.07	2.50	2.09
296	2.13	2.21	3.13	3.42	3.58	3.59	3.53	4.26	5.99	7.17	1.20	1.90	2.01	2.32	2.50	2.49
297	2.22	2.30	3.05	3.27	3.38	3.39	3.34	4.44	5.60	6.44	1.70	2.40	2.57	3.08	3.50	3.32
298	2.39	2.62	3.88	4.42	4.77	4.77	4.63	4.78	9.88	11.26	1.65	2.65	2.77	2.95	3.50	3.01
299	2.58	2.86	4.58	5.93	6.30	6.30	6.11	5.16	12.22	15.17	1.30	2.70	2.77	2.64	3.50	2.50
300	2.64	2.86	5.66	6.67	7.17	7.17	7.01	5.28	14.96	17.39	0.75	2.55	2.58	2.24	3.50	1.95
301	2.64	3.11	5.78	6.84	7.36	7.36	7.15	5.28	15.04	17.37	1.80	3.85	3.92	3.45	4.50	3.10
302	2.43	2.71	3.85	4.35	4.67	4.67	4.52	4.86	8.45	10.61	2.40	3.50	3.67	3.99	4.50	4.09
303	2.05	2.63	2.76	2.94	2.90	2.90	2.87	4.10	8.91	11.41	2.25	3.00	3.25	3.67	4.50	3.80
304	2.43	2.93	4.64	5.68	6.16	6.16	5.95	4.86	12.32	15.22	2.00	3.75	3.87	3.71	4.50	3.56
305	2.49	3.35	5.24	6.16	6.65	6.65	6.42	4.98	12.98	15.70	2.65	4.55	4.67	4.40	5.50	4.20
306	2.61	3.30	6.50	7.69	8.12	8.12	7.95	5.22	16.02	17.51	1.75	4.60	4.68	3.89	5.50	3.36
307	2.02	2.44	3.56	4.22	4.58	4.58	4.39	4.04	8.56	[illegible]	3.25	4.50	4.69	4.95	5.50	5.01
308	2.11	2.64	3.99	4.62	5.02	5.02	4.73	4.22	9.79	12.45	3.50	5.00	5.18	5.30	6.50	5.29
309	2.20	2.85	4.57	5.67	6.34	6.34	6.09	4.41	12.45	15.03	3.25	5.35	5.48	5.17	6.50	4.97
310	2.35	3.27	6.45	7.63	8.00	8.00	7.83	4.70	15.92	16.80	2.00	5.70	5.78	4.64	6.50	3.95
311	2.24	2.45	3.46	3.83	4.04	4.04	3.92	4.48	6.33	7.57	3.75	4.65	5.11	5.78	6.25	5.98
312	2.15	2.89	5.20	6.16	6.62	6.62	6.37	4.30	13.02	15.31	3.35	5.80	5.92	5.46	7.50	5.19
313	2.32	3.19	6.36	7.54	7.91	7.91	7.75	4.64	15.73	16.70	1.85	5.35	5.43	4.37	7.50	3.71
314	1.89	2.55	4.24	4.98	5.42	5.42	5.15	3.78	10.15	12.98	4.10	6.00	6.19	4.21	7.25	6.15
315	1.96	2.69	4.17	4.96	5.28	5.24	5.00	3.92	10.47	13.08	4.80	6.75	6.95	4.92	9.25	6.86
316	1.96	2.84	5.07	6.02	6.49	6.49	6.20	3.92	13.11	15.20	3.95	6.75	6.88	6.29	8.50	6.01
317	2.22	3.22	6.16	7.28	7.67	7.67	7.48	4.44	15.52	16.35	2.25	6.25	6.34	5.11	8.50	4.42
318	1.96	2.48	3.52	4.02	4.35	4.35	4.12	3.92	8.12	10.36	5.00	6.60	6.86	7.29	7.70	7.36
320	2.93	3.02	4.79	5.40	5.76	5.76	5.66	5.86	11.27	13.80	0.65	1.70	1.73	1.69	2.50	1.53
321	2.83	2.98	4.67	5.60	6.06	6.06	5.91	5.66	13.25	16.02	0.70	2.15	2.18	2.02	3.00	1.97
322	3.09	3.28	5.41	6.27	6.78	5.78	6.62	6.18	15.70	18.33	0.70	2.45	2.48	2.14	3.50	1.89
323	2.89	3.15	5.48	6.43	6.58	5.98	6.80	5.78	17.18	18.88	0.50	2.85	2.88	2.39	4.00	2.09
325	2.95	3.45	4.11	4.47	4.72	4.72	4.54	5.90	12.37	12.70	5.15	6.70	5.96	7.36	7.90	7.43

TABLE A-3. (Concluded)

RUN NO.	-------- D.O. CONCENTRATIONS (MG/L) ENTR	VENTURI EXIT	BEND EXIT	PLATE	EXIT (CALC)	EXIT (EXP)	TRUE EXIT -------	D.N. CONC.(MG/L) ENTR	BEND EXIT	TRUE EXIT	---- HEAD RELATIVE TO INLET (FEET) VENTURI EXIT	BEND ENTR	BEND EXIT	PLATE	EXIT (EXP)	TRUE EXIT ----
332	1.66	1.94	5.12	5.81	5.65	5.85	5.82	3.32	8.68	11.49	1.10	2.45	2.52	2.58	3.00	2.55
333	1.73	1.88	6.41	7.37	6.92	7.17	6.93	3.46	11.36	14.54	0.70	2.45	2.48	2.29	3.00	2.35
334	1.54	1.58	2.17	2.30	2.33	3.33	2.32	3.08	3.89	4.44	1.35	2.25	2.36	2.90	3.00	3.08
335	1.44	1.55	3.16	3.13	3.06	3.13	3.05	2.88	4.39	5.40	1.95	2.95	3.11	3.85	4.00	4.06
336	1.44	1.72	3.78	4.57	4.82	4.82	4.71	2.88	7.53	10.08	1.75	3.15	3.27	3.54	4.00	3.58
337	1.42	1.90	6.58	7.68	7.61	7.61	7.52	2.84	11.72	14.97	1.35	3.35	3.42	3.10	4.00	2.89
338	1.65	1.89	8.52	8.74	7.75	9.39	7.76	3.30	13.59	16.55	0.60	3.00	3.03	2.59	4.00	2.32
339	1.90	2.44	8.25	9.28	8.77	8.77	9.92	3.80	14.21	16.68	1.75	4.35	4.42	3.70	5.00	3.32
340	1.90	2.21	7.57	9.19	8.65	8.85	8.94	3.60	15.93	17.43	0.90	4.25	4.29	3.32	5.00	2.97
341	1.80	2.22	5.20	6.71	6.55	6.55	6.43	3.60	10.79	13.70	2.20	4.25	4.37	4.28	5.00	4.16
342	1.65	2.06	3.91	4.70	4.96	4.96	4.82	3.30	7.99	10.35	2.50	4.00	4.18	4.63	5.00	4.71
344	1.68	2.34	6.43	7.77	7.95	7.85	7.81	3.36	14.13	16.12	1.70	5.50	5.57	4.64	6.00	4.23
345	1.60	2.19	4.73	5.80	6.09	6.09	5.92	3.20	10.84	13.63	2.80	5.65	5.77	5.57	6.00	5.44
346	1.27	1.79	3.38	4.15	4.44	4.44	4.26	2.54	7.92	10.54	3.00	5.35	5.52	5.85	5.75	5.87
347	1.27	1.86	3.44	4.22	4.52	4.52	4.33	2.56	8.50	11.22	3.75	5.75	5.93	6.17	6.75	6.17
348	1.34	1.95	4.92	6.05	6.29	6.29	6.15	2.60	10.41	13.26	3.35	6.00	6.12	5.91	7.00	5.79
349	1.57	2.44	6.76	8.13	8.10	8.10	8.10	3.14	14.44	16.04	2.30	6.20	6.28	4.96	7.00	4.41
350	1.57	2.51	7.04	8.45	8.34	9.04	8.38	3.14	14.71	16.21	2.00	6.30	6.38	4.89	9.00	4.27
351	1.56	2.49	5.59	6.22	7.00	7.00	6.89	3.12	12.34	14.68	3.80	6.65	6.77	6.11	8.00	5.95
355	1.59	1.74	5.51	6.36	6.43	6.43	6.39	3.18	10.69	13.59	0.71	3.30	3.03	2.84	3.00	2.71
356	1.59	1.80	5.96	7.07	7.18	7.19	7.13	3.18	12.59	15.50	0.75	3.40	3.43	3.06	3.50	2.84
357	1.57	1.85	4.67	5.07	5.45	5.45	5.30	3.14	14.16	16.25	0.80	3.70	3.73	3.12	4.00	2.80
358	1.57	1.76	7.12	7.55	7.57	7.60	7.64	3.14	12.81	15.79	0.65	3.25	3.28	2.90	4.50	2.69
359	1.57	2.04	7.24	8.66	8.59	8.59	8.60	3.14	15.03	17.43	1.00	4.25	4.29	3.25	5.00	2.72
360	1.55	2.03	7.28	8.69	8.59	8.59	8.61	3.10	16.09	17.30	1.60	4.75	4.79	3.64	5.50	3.09
361	1.67	1.81	6.69	8.90	8.02	9.02	8.01	2.94	14.90	16.87	0.85	4.35	4.38	3.62	5.00	3.24
362	1.22	1.33	3.79	4.03	3.58	4.05	3.98	2.44	5.66	7.56	0.95	2.55	2.62	2.84	2.50	2.99
363	1.38	1.57	3.56	4.73	4.94	4.94	4.86	2.76	7.75	10.43	1.65	3.00	3.07	3.14	3.00	3.12
364	1.30	1.57	4.27	5.24	5.51	5.51	5.40	2.60	9.26	12.23	1.20	3.35	3.42	3.33	3.50	3.24
365	1.38	1.77	4.80	5.54	6.24	6.24	6.11	2.76	11.19	14.16	1.35	3.90	3.97	3.66	4.00	3.47
366	1.38	1.86	5.28	6.54	6.90	6.80	6.61	2.76	12.35	15.13	1.60	4.50	4.57	4.07	4.50	3.80
367	1.38	1.94	5.76	7.09	7.29	7.29	7.20	2.76	13.07	15.64	1.75	4.90	4.97	4.31	5.00	3.99
368	1.44	2.12	6.12	7.49	7.62	7.62	7.55	2.98	13.69	15.91	1.65	5.35	5.43	4.57	5.50	4.19
369	1.67	2.44	6.74	8.10	8.09	8.09	8.09	3.34	14.51	16.10	1.75	5.90	5.97	4.92	6.00	4.33
370	1.50	2.24	6.26	7.64	7.75	7.75	7.70	3.00	14.13	16.06	1.95	5.35	5.42	4.39	6.00	3.92
371	1.58	2.41	6.70	8.06	8.04	8.04	8.04	3.16	14.25	16.00	2.05	5.80	5.88	4.71	6.50	4.21
372	1.47	2.20	6.17	8.18	8.07	8.07	8.11	2.94	14.05	15.85	1.95	5.80	5.87	4.80	7.00	4.34
373	1.40	2.21	6.62	8.00	7.99	7.99	7.98	2.80	14.28	16.01	1.75	5.45	5.52	4.32	7.50	3.79
374	1.38,	1.82	4.42	5.95	5.96	5.96	5.83	3.06	14.53	17.06	0.68	2.70	2.73	2.16	2.80	1.82
375	1.53	1.91	4.40	5.54	5.96	5.96	5.83	3.06	15.79	17.81	0.68	2.70	2.73	1.95	2.90	1.49
376	1.31	1.40	2.66	2.54	3.00	3.04	2.98	2.62	4.37	5.51	1.40	2.25	2.36	2.88	3.00	3.04
377	1.38	1.59	4.24	4.73	4.75	4.75	4.73	2.76	6.31	8.46	1.60	2.80	2.92	3.31	3.50	3.40
378	1.38	1.70	4.22	5.11	5.35	5.35	5.24	2.76	8.04	10.83	1.75	3.15	3.26	3.47	4.00	3.49
379	1.55	2.06	4.91	5.91	6.21	6.21	6.07	3.10	10.24	13.38	1.95	3.70	3.82	3.80	4.50	3.72
380	1.73	2.31	5.21	6.36	6.65	6.65	6.51	3.46	11.15	14.24	2.10	4.20	4.32	4.21	5.00	4.09
381	1.71	2.32	5.30	6.47	6.75	6.75	6.61	3.42	11.41	14.44	2.50	4.65	4.77	4.58	5.50	4.44
382	1.71	2.34	5.37	6.56	6.83	6.83	6.69	3.42	11.57	14.58	2.80	5.00	5.12	4.89	6.00	4.75
383	1.71	2.39	5.68	6.93	7.17	7.17	7.04	3.42	12.16	15.08	2.90	5.40	5.52	5.16	6.50	4.98
384	1.79	2.54	5.55	7.23	7.43	7.43	7.31	3.58	12.57	15.36	3.15	5.80	5.92	5.49	7.00	5.28
385	1.78	2.58	6.07	7.35	7.53	7.53	7.42	3.56	12.80	15.46	3.35	6.25	6.37	5.84	7.50	5.62
386	1.78	2.66	6.14	7.44	7.61	7.61	7.50	3.56	13.13	15.63	3.75	6.85	6.98	6.32	8.00	6.08
387	1.45	1.49	1.55	1.56	2.00	2.50	1.98	2.90	3.42	3.77	1.60	2.55	2.73	3.60	3.50	3.95
388	1.45	1.56	2.57	2.84	2.90	2.90	2.87	2.90	4.24	5.15	1.65	3.00	3.17	3.96	4.00	4.17
389	1.45	1.66	2.93	3.44	3.62	3.62	3.53	2.90	5.57	7.22	2.15	3.35	3.52	4.15	4.50	4.30
390	1.43	1.74	3.01	3.50	3.83	3.83	3.71	2.86	6.42	8.47	2.65	4.00	4.18	4.75	5.00	4.95
391	1.43	1.84	3.27	3.55	4.22	4.22	4.07	2.86	7.43	9.83	2.65	4.50	4.68	5.11	5.50	5.18
392	1.43	1.91	3.50	4.25	4.54	4.54	4.37	2.86	8.11	10.70	3.25	4.95	5.12	5.46	6.00	5.49
393	1.34	1.86	3.55	4.36	4.65	4.65	4.47	2.64	8.30	10.98	3.50	5.25	5.42	5.69	6.50	5.70
394	1.34	1.92	3.74	4.59	4.89	4.89	4.71	2.68	8.63	11.35	3.75	5.65	5.83	6.06	7.00	6.06
395	1.34	2.00	3.37	4.89	5.20	5.20	5.02	2.63	9.11	11.93	4.00	5.10	5.28	5.47	7.50	5.44
396	1.34	2.05	4.04	4.97	5.28	5.28	5.09	2.58	9.35	12.16	4.35	5.65	5.84	5.99	8.00	5.95
397	1.73	2.23	3.58	4.25	4.49	4.49	4.31	3.46	7.72	9.93	4.60	6.50	6.75	7.42	8.00	7.50
398	1.50	1.94	3.23	3.96	4.10	4.10	3.94	3.00	6.93	9.06	3.90	5.60	5.93	6.53	7.00	6.63
400	1.89	2.16	3.05	3.49	3.59	3.69	3.57	3.78	6.66	8.44	3.00	4.35	4.59	5.52	6.00	5.70
401	1.79	2.25	3.47	4.11	4.38	4.38	4.20	3.58	8.23	10.80	3.85	5.40	5.64	6.39	7.00	6.51
402	1.79	2.38	3.90	4.67	4.98	4.98	4.76	3.58	9.15	11.99	4.65	6.55	6.80	7.45	8.00	7.57

APPENDIX B

FULL-SCALE U-TUBE EXPERIMENTAL DATA

This appendix contains experimental data, plus mass transfer coefficients calculated from the data, for full-scale U-tube installations at Jefferson Parish, Louisiana, and Port Arthur, Texas. The data are presented in three tables, the contents of which are described in the following paragraphs.

Table B-1 contains the experimental data obtained at the two U-tube sites in Jefferson Parish, Louisiana. Series 500 run numbers were assigned to data for location 5, and series 700 run numbers correspond to data for location 7. Q_w is the water flowrate; y is the air-to-water volume fraction at 1 atm and 77°F. Initial oxygen demand for the influent ($IDOD_i$) and dissolved oxygen for the effluent ($D.O._e$) were determined by the Winkler method. The influent dissolved oxygen levels and effluent IDOD levels had been spot checked and found to be consistently zero. Total oxygen transfer was then determined by adding $IDOD_i$ and $D.O._e$.

Static heads (H) at the various stations are given in inches of water, referenced to the elevation of the venturi centerline. These values may be converted to absolute pressures by the relationship:

$$p = H + z + p_o$$

where z is the distance between the venturi centerline and the station pressure tap (see Fig. 18 and 19 for dimensions) and p_o is the ambient pressure. For example, for run 500, the value given for $H_3 = 48$ means that the static head at station 3 is 48 inches of water above the aspirator centerline and the absolute pressure at station 3 (if $p_o = 1$ atm) is 4.0 + 0 + 34.0 = 38.0 feet of water; the value of $H_7 = -98$ means that the static head at station 7 is 98 inches of water below the aspirator centerline and the absolute pressure is -8.2 + 39.0 + 34.0 = 64.8 feet of water. It should be noted that head measurements at station 9 for location 5 were not obtained, because this test port became plugged during the U-tube installation and could not be cleared. The mass transfer coefficients (K_L) were calculated from the other data using the data reduction program as described in Section VII of this report. It can be noted that some tests were made to obtain pressure drop information alone, without making oxygen measurements.

Tables B-2 and B-3 contain the field test data obtained at the Pioneer Park lift station, Port Arthur, Texas. Dissolved oxygen determinations at this location were conducted using the 15-minute modified Winkler method (azide). The total oxygen transfer in the U-tube was calculated as: $D.O._e + IDOD_i - IDOD_e$.

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TABLE B-1. JEFFERSON PARISH U-TUBE EXPERIMENTAL DATA

Run No.	Q_N, gpm	y at 1 atm, 77 F (volume fraction)	$IDOD_i$, mg/ℓ	$D.O._e$, mg/ℓ	Oxygen Transfer, mg/ℓ	Head Relative to Venturi Centerline, inches of water						$K_L \times 10^3$ at 20 C, ft/sec
						Station 3	Station 5	Station 6	Station 7	Station 9	Station 10	
500	1040	0.086	0.2	4.6	4.8	48	8	-21	-98	-	-91	0.416
501	2090	0.039	-	1.9	-	-26	-85	-81	-	-	-	0.606
502	2090	0.036	-	-	-	-35	-79	-76	-90	-	-85	-
503	2000	0.071	2.0	3.6	5.6	-5	-29	-66	-31	-	-28	1.01
504	2000	0.071	-	-	-	19	-37	-66	-37	-	-37	-
505	2000	0.093	1.4	4.8	6.2	39	3	-15	-17	-	-17	0.971
506	2000	0.112	3.5	-	-	77	34	-5	-29	-	-25	-
507	1280	0.099	2.6	3.8	6.4	35	-18	-44	-37	-	-31	0.517
508	1280	0.099	-	-	-	37	-16	-47	-36	-	-31	-
509	1040	0.158	-	5.6	-	48	5	-40	-51	-	-40	0.416
510	1600	0	-	-	-	-	-104	-106	-109	-	-110	-
511	1550	0	-	-	-	-	-113	-110	-111	-	-108	-
512	1230	0.121	1.7	6.0	7.7	34	4	-7	-66	-	-61	0.671
513	1060	0.123	-	-	-	45	3	-39	-61	-	-59	-
514	1380	0.073	0.2	4.3	4.5	-39	-55	-48	-77	-	-69	0.597
515	1360	0.082	-	-	-	-42	-63	-44	-71	-	-72	-
516	1240	0.090	-0.1	5.0	4.9	-57	-63	-64	-84	-	-80	0.514
517	1520	0.037	0.8	2.5	3.3	-83	-108	-92	-76	-	-119	0.829
518	1420	0.040	-	-	-	-85	-105	-92	-74	-	-115	-
519	1950	0.107	0.8	5.7	6.5	90	-10	23	-42	-	-118	0.982
520	1900	0.110	-	-	-	85	27	-1	-55	-	-99	-
521	1570	0	-	-	-	-67	-99	-93	-99	-	-95	-
522	1560	0	-	-	-	-82	-104	-104	-90	-	-101	-
523	840	0.169^a	1.2	6.7	7.9	201	150	121	-124	-	-56	0.372
524	850	0.167^a	-	-	-	201	145	101	-134	-	-65	-
525	800	0.271^a	1.8	6-8	8.6	258	227	223	-151	-	-66	-
526	360	0.623^a	-	-	-	319	278	240	-151	-	-66	-
527	320	0.701^a	-	-	-	319	283	240	-149	-	-68	-
528	550	0.544^a	0.9	8.1	9.0	326	287	241	-136	-	-69	-
529	430	0.696^a	-	-	-	325	284	242	-139	-	-70	-
530	260	1.151^a	-	-	-	326	286	246	-135	-	-70	-
531	1280	0.189^a	0.9	8.2	9.1	340	285	245	-123	-	-55	1.10
532	1540	0.194^a	-	-	-	339	284	242	-124	-	-55	-
533	1580	0.284^a	0.6	8.3	8.9	343	277	236	-141	-	-93	0.701
534	1540	0.291^a	-	-	-	351	278	238	-141	-	-93	-

[a] Compressor in use for supercharging

TABLE B-1. (Concluded)

Run No.	Q_h, gpm	y at 1 atm, 77 F (volume fraction)	$IDOD_i$, mg/ℓ	$D.O._e$, mg/ℓ	Oxygen Transfer, mg/ℓ	Head Relative to Venturi Centerline, inches of water						$K_L \times 10^3$ at 20 C, ft/sec
						Station 3	Station 5	Station 6	Station 7	Station 9	Station 10	
535	1830	0.114	0.9	5.5	6.4	84	22	-15	-110	-	-117	0.816
536	1940	0.077	1.2	3.5	4.7	-8	-74	-81	-105	-	-90	0.737
537	1940	0.066	0.6	4.1	4.7	5	-58	-75	-90	-	-85	0.957
538	1940	0.042	0.5	1.9	2.4	-19	-79	-82	-90	-	-93	0.596
539	1980	0.040	-	-	-	-27	-78	-82	-87	-	-94	-
540	1900	0.039	-	-	-	-	-81	-85	-90	-	-96	-
541	1920	0.062	0.5	3.0	3.5	-10	-76	-81	-90	-	-94	0.647
542	2030	0.059	-	-	-	-11	-75	-81	-91	-	-96	-
543	1950	0.061	-	-	-	-	-75	-81	-94	-	-96	-
544	2000	0.021	-0.7	1.8	1.1	-45	-87	-83	-88	-	-96	0.572
545	2020	0.020	-	-	-	-43	-83	-83	-88	-	-94	-
546	1940	0.020	-	-	-	-	-82	-82	-88	-	-95	-
547	2000	0	-	-	-	-61	-87	-82	-87	-	-95	-
548	2020	0	-	-	-	-	-85	-90	-85	-	-94	-
549	2160	0	-	-	-	-63	-85	-90	-83	-	-92	-
700	620	0	-	-	-	-51	-82	-69	-94	-64	-63	-
701	535	0	-	-	-	-71	-82	-69	-94	-69	-63	-
702	520	0	-	-	-	-68	-80	-67	-90	-76	-87	-
703	580	0	-	-	-	-69	-80	-74	-92	-80	-91	-
704	610	0	-	-	-	-69	-80	-74	-93	-79	-90	-
705	190	0.209	0.0	6.0	6.0	53	-13	-23	-96	-99	-108	-
706	190	0.209	-	-	-	61	-13	-23	-95	-101	-109	-
707	795	0.042	1.2	3.4	4.6	17	-53	-54	-89	-73	-93	1.14
708	890	0.038	-	-	-	12	-52	-53	-87	-75	-90	-
709	770	0.083	1.2	5.1	6.3	100	-3	-22	-89	-87	-95	0.795
710	795	0.075	-	-	-	100	-1	-21	-92	-88	-96	-
711	830	0.072	-	-	-	-	-10	-20	-91	-92	-101	-
712	840	0	-	-	-	-41	-60	-59	-92	-62	-81	-
713	890	0	-	-	-	-40	-62	-63	-90	-66	-80	-

TABLE B-2. PORT ARTHUR U-TUBE EXPERIMENTAL DATA

Run No.	Q_w, gpm	y at 1 atm, 77 F (volume fraction)	$IDOD_i$, mg/ℓ	$IDOD_e$, mg/ℓ	$D.O._e$, mg/ℓ	Oxygen Transfer, mg/ℓ	Head Relative to Pump Centerline, feet of water						$K_L \times 10^3$ at 20 C, ft/sec
							Station 1	Station 4	Station 6	Station 7	Station 9	Station 10	
807	1400	0	--	--	--	--	24.0	23.3	23.4	23.4	23.0	23.0	--
819	1379	0.043	--	--	--	--	24.5	23.8	23.5	23.2	22.6	22.9	--
820	1386	0.011	7.70	--	0	--	23.8	23.5	23.4	23.3	22.9	22.6	--
821	1379	0.022	7.70	--	0	--	24.1	23.6	23.4	23.2	22.8	22.7	--
822	1365	0.033	7.70	--	0	--	24.2	23.7	23.4	23.1	22.6	22.6	--
823	1344	0.045	6.50	--	0	--	24.3	23.8	23.3	22.9	22.4	22.3	--
824	1386	0.011	6.50	6.20	0	0.30	--	23.5	--	--	--	23.6	0.324
825	1379	0.022	7.40	5.90	0	1.50	--	23.6	--	--	--	22.7	0.896
826	1379	0.033	7.10	5.00	0	2.10	--	23.7	--	--	--	22.6	0.870
827	1379	0.054	9.03	4.78	0	4.25	25.0	24.3	23.5	23.1	22.6	22.7	1.06
828	1344	0.078	9.03	5.70	0	3.33	27.8	24.8	23.4	22.9	22.3	22.3	0.531
829	1120	0.094	8.73	6.30	0	2.43	29.6	27.5	22.2	21.8	21.2	21.3	0.263
830	1127	0.066	9.33	6.78	0.80	3.35	26.1	24.3	22.4	21.9	21.5	21.4	0.513
831	1113	0.040	10.02	7.52	0.60	3.10	21.9	21.8	22.2	21.8	21.4	21.2	0.741
832	1120	0.013	9.33	7.52	0	1.81	20.6	21.2	22.1	22.0	21.9	21.2	1.44
833	833	0.018	9.33	7.57	0	1.76	19.4	20.1	21.1	21.0	20.8	20.2	0.714
834	833	0.054	9.03	8.60	0	0.43	22.0	21.7	21.3	20.8	20.4	20.3	0.517
835	833	0.090	--	--	--	--	27.7	27.3	21.3	20.7	20.3	20.2	--
836	833	0.090	6.91	1.42	1.2	6.69	29.8	28.9	21.4	20.6	20.1	20.3	0.809
837	833	0.126	6.91	1.42	0.9	6.39	31.0	30.3	22.9	20.4	19.9	20.1	0.538
838	574	0.182	6.30	0	3.2	9.5	34.8	33.3	26.0	19.6	18.7	19.7	0.523
839	581	0.129	--	--	--	--	31.6	26.3	24.2	19.6	19.4	20.3	--
840	567	0.132	5.70	1.75	1.80	5.75	33.1	31.2	23.5	20.1	19.7	19.8	0.498
841	567	0.132	2.20	0	2.20	4.40	32.2	28.2	23.8	20.2	19.6	20.1	0.321
842	581	0.026	2.90	1.5	2.30	3.7	29.8	28.4	21.2	20.4	19.5	20.3	--
843	315	0.048	2.60	0	1.70	4.30	--	27.8	--	19.9	19.8	19.8	0.530
844	378	0.277	6.30	0.12	0	6.18	36.6	25.3	25.3	19.8	18.2	19.9	0.132
845	399	0.187	8.13	4.18	4.20	8.15	33.4	23.3	23.2	19.0	19.1	19.7	0.237
846	406	0.111	6.92	3.94	3.70	6.68	31.7	28.5	23.7	19.5	19.5	20.0	0.323
847	399	0.038	5.70	4.33	3.80	5.17	31.3	26.2	22.3	19.4	19.3	20.1	0.536
848	588	0.051	7.22	5.88	2.90	4.24	25.8	21.6	22.0	19.8	19.8	20.4	0.547
849	574	0.130	6.30	3.85	3.60	6.05	31.4	25.5	21.4	19.6	19.6	20.4	0.352

The meaning of the static head columns is identical to that explained above for Table B-1. Figure 25 gives the physical dimensions of the U-tube system and locations of the stations.

Table B-3 contains total sulfide data obtained from five runs at the Port Arthur installation. Standard chemical methods (Ref. 34) were utilized for these on-site determinations.

TABLE B-3. PORT ARTHUR TOTAL SULFIDE CONCENTRATION DATA

Run No.	Q_W, gpm	y_o at 1 atm, 77°F (volume fraction)	Total Sulfides Influent (mg/ℓ)	Total Sulfides Effluent (mg/ℓ)	Percent Reduction
827	1379	0.054	2.0	0.4	80
831	1113	0.040	1.6	0.2	87
834	833	0.054	1.5	0.5	66
837	833	0.013	0.8	0.6	25
840	567	0.132	0.6	0.4	33

APPENDIX C

U-TUBE DESIGN PROGRAM

This appendix contains a listing of the U-tube design program developed during this project, complete instructions for preparing input data cards, and sample input data. Engineering and computational details about the program are given in Section VIII, U-tube Design; samples of the program output are given in Appendix D.

As previously discussed in the U-tube Design section, the program in its current form can make analyses for three major configurations or problem types: (1) aspirated-air U-tubes installed in the end of a force main (i.e., full-flowing pipe under pump head); (2) compressed-air U-tubes installed in a force main; and (3) eductors, which are essentially compressed-air U-tubes with the diffuser located at the bottom of the up-leg. These are indicated by the value of KTYPE (1, 2, or 3 for the three cases, respectively), which is one of the input variables.

Three types of input data cards are used to supply the required information to the program. The first two types (called General Information and Problem Type cards) are identical in format for all three problem types. The third type of input data card (called a Case card) is different for each of the problem type options. Multiple cases may be run. Blank cards are used to terminate the reading of one card type and step back to the previous card type in the input sequence. The input data cards described below, in the order in which they must appear in the data deck.

General Information Card (actually 2 cards - FORMAT 12F6.1/3F6.4, I2)

Variables marked with a superscript 2 can be left blank for KTYPE = 2; Variables marked with a superscript 3 can be left blank for KTYPE = 3.

$ANGC^{2,3}$	Full-cone angle of aspirator contraction section, degrees
$ANGE^{2,3}$	Full-cone angle of aspirator diffuser section,degrees
ELR	Centerline-to-face distance for pipe elbows divided by nominal pipe diameter (normally 1.5 for long-radius or 1.0 for standard radius elbows)

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ELK	Normal loss coefficient for pipe elbows, expressed as one-phase loss in velocity heads (normally 0.46 for long-radius or 0.75 for standard-radius elbows)
F21[2,3]	Length of straight pipe spool downstream of aspirator (see Fig. 44) divided by pipe diameter
F22[2,3]	Length of straight pipe spool upstream of aspirator (see Fig. 44) divided by pipe diameter
USDOWN	Slip velocity in downward flow, ft/sec (normally use results from this project, 0.2 ft/sec)
USUP	Slip velocity in upward flow (opposite sign convention to USDOWN so that it is also positive), ft/sec (normally use results from this project, 0.2 ft/sec)
XIDOWN	Air-water interfacial area per unit volume of air in down-leg, 1/ft (normally use results from this project, 470./ft)
XIUP	Air-water interfacial area per unit volume of air in up-leg, 1/ft (normally use results from this project, 470./ft)
PEXTRA[2,3]	Difference between ambient pressure and aspirator throat pressure, calculated on one-phase basis, ft water (normally use about 3-4 ft water)
ALPHA	Ratio of mass transfer coefficient for waste water of interest to mass transfer coefficient of "tap water" (normally use about 0.9 for treated effluent, 0.8 for not seriously septic sewage)
DPTOL	Tolerance within which the exit pressure must match the specified value before the iteration procedure will terminate (for most purposes, a value of about 0.01 ft water is a good value to use)
HTEST	Tolerance within which the numerical root-solving procedure in subroutine HERSHY must converge (a value of about 0.001 is recommended)
STPSZ	Stepsize for the finite-difference calculations along the U-tube path, ft (for most cases, the results for the numerical integration are effectively constant for STPSZ below 0.5 ft down to such small values that roundoff errors begin to become important; a value of about 0.1 ft is recommended for routine calculations)

KTOP	Maximum number of iterations permitted in converging to required criterion (most cases have converged, with DPTOL approximately 0.01 ft water, in 2 to 8 iterations; therefore, a value of about 20 for KTOP is recommended)

Problem Type Card (FORMAT 3I1, 2X, F5.1, 6F10.2)

KTYPE	Gate number which indicates the problem type: 1 for aspirated-air U-tube, 2 for compressed-air U-tube, 3 for an eductor
IPR	Gate number which permits printing intermediate output at the end of each iteration if IPR = 1; otherwise leave blank
JPR	Gate number which permits printing intermediate output at the end of each numerical integration step in each of the iterations if JPR = 1; otherwise leave blank
A10	Distance from grade down to incoming pipe centerline (see Fig. 44 for diagram), ft
A16	Distance of horizontal exit spool (see Fig. 44), ft
D2	Inside diameter of incoming pipe, inch
D9	Inside diameter of up-leg pipe, inch
PAMB	Ambient pressure, ft water (1 atmosphere = 34.0 ft water at 77 F)
T	Water temperature, F
C1	Inlet D.O. concentration minus immediate oxygen demand, mg/liter

Case Card, if KTYPE = 1 (FORMAT 6F10.2, I1, F9.1)

A18	Distance from incoming pipe centerline up to aspirator centerline, ft
A19	Distance from incoming pipe centerline down to outlet pipe centerline, ft
Y0	Initial air-to-water volume fraction at 68 F, 1 atmosphere
A11	Depth of casing bottom below grade, ft
D6	Inside diameter of down-leg pipe, inch

QW	Water flow rate, gal./min
KE	Gate number set to 0 is E is to be calculated by program, and set to 1 if E is to be read as input data
E	(When KE=1) Specified venturi aspirator contraction area ratio, i.e., cross-sectional area of incoming pipe divided by area of aspirator throat

Case Card, if KTYPE = 2 (FORMAT 6F10.2)

D6	Inside diameter of down-leg pipe, inch
A19	Distance from incoming pipe centerline down to outlet pipe centerline, ft
Y0	Initial air-to-water volume fraction at 68 F, 1 atmosphere
A11	Depth of casing bottom below grade, ft
A25	Distance from bottom of entrance elbow to bottom of diffuser ring (see Fig. 45 for diagram), ft
QW	Water flow rate, gal./min

Case Card, if KTYPE = 3 (FORMAT 4F10.2, I1, F9.2)

A19	Distance from incoming pipe centerline down to outlet pipe centerline, ft
Y0	Initial air-to-water volume fraction at 68, 1 atmosphere
A11	Depth of casing bottom below grade, ft
QW	Water flow rate, gal./min
KP	Gate number set to 0 if P9 is to be calculated by program, and set to 1 if P9 is to be read as input data
P9	Pressure at bottom of eductor (Station 9 in Fig. 45), ft water absolute

As many Case cards as desired can be placed in series. If one blank card is placed after a Case card, the program will next expect a Program Type card, followed by Case cards. If two blank cards are placed after a Case card, the program will next expect a General Information Card, followed by a Problem Type card and Case cards. There should not be a blank card immediately following a General Information Card or a Problem Type card.

Table C-1 presents a listing of a sample data deck. Included are examples of each of the KTYPE options and branching-back options, by use of blank cards.

Following Table C-1 is a listing of the U-tube design program.

TABLE C-1. SAMPLE INPUT DATA DECK FOR U-TUBE DESIGN PROGRAM

```
50.     15.     1.0     .75   1.      2.      .2      .2      470.  470.  3.      .80
.01     .001    .2      10                                                            00000010
1    0.   0.            23.25         23.25       34.         68.         0.          00000020
0.        3.            .10           40.5        23.25       3470.       1    7.72   00000030
0.        0.            .10           50.5        23.25       3470.       1    7.72   00000040
0.        3.            .10           50.5        23.25       3470.       1    7.72   00000050
0.        3.            .20           50.5        23.25       3470.       1    7.72   00000060
                                                                                      00000070
2    0.   0.            23.25         29.0        34.         68.         0.          00000080
23.25     0.            .05           20.0        0.          3472.                   00000090
23.25     0.            .10           20.0        0.          3472.                   00000100
23.25     0.            .15           20.0        0.          3472.                   00000110
23.25     0.            .20           20.0        0.          3472.                   00000120
23.25     0.            .25           20.0        0.          3472.                   00000130
                                                                                      00000140
                                                                                      00000150
60.     22.     1.0     .75   0.      0.      .2      .2      470.  470.  3.      .9  00000160
.01     .001    .1      10                                                            00000170
11    4.0  12.          12.           13.25       34.         75.         -.8         00000180
3.0        6.5          .05           44.25       19.         1900.       1 3.52      00000190
3.0        6.5          .1            44.25       19.         1900.       1 3.52      00000200
                                                                                      00000210
31    3.5  0.           12.           13.25       34.         82.4        .2          00000220
8.         .15          30.           1800.                                           00000230
                                                                                      00000240
```

```
C
C        DESIGN PROGRAM FOR IN-LINE AERATOR SYSTEMS
C              KTYPE=1 FOR ASPIRATED-AIR U-TUBE
C              KTYPE=2 FOR COMPRESSED-AIR U-TUBE
C              KTYPE=3 FOR EDUCTOR
C
C        THIS IS MAIN PROGRAM.   ALSO NEEDED ARE SUBROUTINES COEFF,
C        ENTR, HERSHY, INTRO, CUT, AND STEP ...
C        PLUS FUNCTIONS AL, DPD, AND HL
C
C     ******************************************************************
      COMMON AIT3,AKL,ALPHA,AV,A3,A9,A10,A11,A15,A16,A18,A19,A24,A25,
     1 AEL2,AEL9,ANGC,ANGE, C,CN,CS,CSN,CSR,CSNR,C1,C5,C6,C7,C8,C9,C10,
     2 C12,CN1,CN5,CN6,CN7,CN8,CN9,CN10,CN12,CS1,CS5,CS6,CS7,CS8,CS9,
     3 CS10,CS12,CSN1,CSN5,CSN6,CSN7,CSN8,CSN9,CSN10,CSN12, DP,DP1,DP2,
     4 DPDL,D2,D6,D9, E,FLK,FLR,F21,F22,H,HD,HH,HH5,HLD,HTEST,HU,
     5 IPR,I1,JPR,KF,KL,KLN,KP,KTOP,KTYPE, NSD,NSH,NSH5,NSU, PAMB,
     6 PEXTRA,PTOL,P13,P15,P19, P0,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P12,
     7 QW,R,STPSZ,T,TC, UM2,UM6,UM9,USDOWN,USUP,UW2,UW6,UW9,VDIF,
     8 XIDOWN,XIUP,XKL2,XKL6,XKL9,XN2,XNN2, Y0,Y1,Y2,Y5,Y6,Y7,Y8,Y9,
     9 Y10,Y12, A31,AEL6,D12,KOUNT
     1  ,IFRST
      COMMON/PASSX/IPASS,IERR
      DIMENSION IBLNK(142)
      EQUIVALENCE (IBLNK(1),AIT3)
C
      REAL KL,KLN
      DO 10 I=1,142
   10 IBLNK(I)=0
  100 READ(5,950)ANGC,ANGE,FLR,FLK,F21,F22,USDOWN,USUP,XIDOWN,XIUP,
     1PEXTRA,ALPHA,DPTOL,HTEST,STPSZ,KTOP
  950 FORMAT(12F6.1/3F6.4,I2)
      ANGC=ANGC*3.1416/180.
      ANGE=ANGE*3.1416/180.
  101 READ(5,951)KTYPE,IPR,JPR,A10,A16,D2,D9,PAMB,T,C1
      IFRST=15
  951 FORMAT(3I1,2X,F5.1,6F10.2)
      IF(KTYPE)101,100,1011
 1011 IF(KTYPE-3)1012,1012,101
 1012 TC=(T-32.)/1.8
      CSR=187.6/T**.714-.16
      CSNR=242.0/T**.6+.07

      D2=D2/12.
      D9=D9/12.
  250 GO TO(104,107,112),KTYPE
  104 READ(5,952)A18,A19,Y0,A11,D6,QW,KE,E
  952 FORMAT(6F10.2,I1,F9.1)
      IF(A11-5.)101,101,118
  107 READ(5,954)D6,A19,Y0,A11,A25,QW
  954 FORMAT(6F10.2)
      IF(A11-5.)101,101,118
  112 READ(5,956)A19,Y0,A11,QW,KP,P9
  956 FORMAT(4F10.2,I1,F9.2)
      IF(A11-5.)101,101,118
C
C           PRELIMINARY CALCULATIONS AND 1-PHASE ZONE
C
  118 D6=D6/12.
      IERR=0
      CALL INTRO
  120 GO TO(122,124,126),KTYPE
  122 A21=F21*D2
      IF(A21-STPSZ*4.)1221,1221,1222
 1221 HH5=A21
      NSH5=1
      GO TO 124
 1222 NSH5=IFIX(A21/STPSZ/4.+.5)
      HH5=A21/NSH5
  124 NSD=IFIX(A9/STPSZ+.5)
      HD = A9
      IF(NSD.GT.0) HD = A9/NSD
  126 NSU=IFIX(A15/STPSZ+.5)
      HU=A15/NSU
      IF(A16-.1)138,138,128
  128 IF(A16-STPSZ*4.)130,130,132
  130 HH=A16
      NSH=1
      GO TO 138
  132 NSH=IFIX(A16/STPSZ/4.+.5)
      HH=A16/NSH
C
  138 KOUNT=0
      ITM=0
      XP3=0.
      XDP=0.
      XR=0.
C
C          CALCULATIONS FROM STATION 3 TO 6
C
  140 KOUNT=KOUNT+1
      CALL COEFF
  142 CALL ENTR
      IF(IERR.GT.0)  GO TO 250
C
C          DOWN-LEG CALCULATIONS
C
      IF(KTYPE-2)150,150,220
  150 H=HD
      DO 180 J=1,NSD
      UM6=UM6*(1.+Y2)
      CALL STEP(1)
      IF(C+20.)177,177,178
  177 WRITE(6,9001)C,P1,P2,Y1,Y2
 9001 FORMAT('   C IS OUTSIDE (-20,50) IN DOWN-LEG'/'     C,P1,P2,Y1,Y2
     1= ',5F12.5)
      GO TO(104,107,112),KTYPE
  178 IF(C-50.)180,177,177
  180 CONTINUE
      P7=P2
      C7=C
      CN7=CN
      CS7=CS
      CSN7=CSN
      Y7=Y2
C
C          REDUCER AND RETURN BEND
C
      UM6=UM6*(1.+Y7)
      UM9=UM9*(1.+Y2)
  200 IF(IFIX(A31+.6))204,204,202
  202 P8=P7+DPD(A31,Y2)-.04*UM9*UM9/64.348
      H=A31/2.
      HLD=(P8-P7)/2.
      CALL STEP(3)
      CALL STEP(3)
      C8=C
      CN8=CN
      CS8=CS
      CSN8=CSN
      Y8=Y2
      GO TO 206
  204 C8=C7
      CN8=CN7
      P8=P7
      CS8=CS7
      CSN8=CSN7
      Y8=Y7
C
  206 HLD=2.*FLK*(UM9*(1.+Y2))**2/64.348
      P9=P8-HLD
      PM=(P9+P8)/2.
      CS=CS*PM/P8
      CSN=CSN*PM/P8
      CALL STEP(4)
      C9=C
      CN9=CN
      CS9=CS
      CSN9=CSN
      Y9=Y2
C
C          UP-LEG CALCULATIONS
C
  220 H=HU
      DO 300 J=1,NSU
      CALL STEP(2)
      IF(C+20.)240,240,298
  240 WRITE(6,9240)C,P1,P2,Y1,Y2
 9240 FORMAT('   C IS OUTSIDE (-20,50) IN UP-LEG'/'     C,P1,P2,Y1,Y2 =
     1',5F12.5)
      GO TO(104,107,112),KTYPE
  298 IF(C-50.)300,240,240
  300 CONTINUE
      P10=P2
      C10=C
      CN10=CN
      CS10=CS
      CSN10=CSN
      Y10=Y2
```

```
C
C         EXIT ELBOW AND HORIZONTAL SPOOL CALCULATIONS
C
      IF(A16-.1)322,322,310
  310 UM9=UM9*(1.+Y2)
      HLD = AEL9/(1.+Y2)+ELK*UM9*UM9/64.348
      P11=P10-HLD
      PM=(P11+P10)/2.
      CS=CS*PM/P10
      CSN=CSN*PM/P10
      CALL STEP(5)
C
      H=HH
      DO 320 J=1,NSH
  320 CALL STEP(6)
  322 P12=P2
      C12=C
      CN12=CN
      CS12=CS
      CSN12=CSN
      Y12=Y2
C
C         TEST CONVERGENCE AND CALCULATE NEW ENTRANCE PRESSURE
C
      DP=P12-PAMB
      DPA=ABS(DP)
      GO TO(345,335,325),KTYPE
  325 IF(KP)620,326,620
  326 IF(DPA-20.)328,328,327
  327 DPA=20.
  328 P9=P9-SIGN(DPA,DP)
      P1=P9+P19
      NAMELIST/RC9/P1,P9,P10,P12,C1,C9,C10,C12,CN1,CN9,CN10,CN12,CS12,
     A CSN12,Y12,P19,DP
      IF(KOUNT-KTOP)330,330,600
  330 IF(DPA-DPTOL)620,331,331
  331 IF(IPR)140,140,332
  332 WRITE(6,RC9)
      GO TO 140
C
  335 IF(DPA-20.)337,337,336
  336 DPA=20.
  337 P5=P5-SIGN(DPA,DP)
      P1=P5+P15
      NAMELIST/RC5/P5,P6,P7,P8,P9,P10,P12,C1,C5,C6,C7,C8,C9,C10,C12,CN1,
     A CN5,CN6,CN7,CN8,CN9,CN10,CN12,CS12,CSN12,Y12,P15,P1,DP
      IF(KOUNT-KTOP)338,338,600
  338 IF(DPA-DPTOL)620,339,339
  339 IF(IPR)140,140,340
  340 WRITE(6,RC5)
      R=.01
      GO TO 140
C
C         CALCULATE IMPROVED ESTIMATE FOR P3 TO MATCH P(EXIT)
C         FOR KTYPE=1  (TO STATEMENT 600)
C
  345 P1=P3+P13
      NAMELIST/RCM/P1,P3,P4,P5,P6,P7,P8,P9,P10,P12,C1,C5,C6,C7,C8,C9,C10
     A,C12,CN1,CN5,CN7,CN10,CN12,CS12,CSN12,Y12,P13,DP,E,R,XP3,XDP,XR
      IF(E-1.0001)351,351,352
  351 R=0.
      GO TO 353
  352 R=(P3-P5)/(P3-P4)
  353 IF(KOUNT-KTOP)354,354,600
  354 IF(DPA-DPTOL)620,355,355
  355 IF(IPR)357,357,356
  356 WRITE(6,RCM)
  357 IF(ITM-1)358,450,500
  358 ITM=1
  359 XP3=P3
      XDP=DP
      XR=R
      XDPA=DPA
  360 IF(KE)368,368,362
  362 IF(R-.8)370,370,364
  364 IF(R-1.2)365,365,366
  365 R=.8
      GO TO 370
  366 TP=.7*DP
      GO TO 371
  368 IF(R-.99)  370,370,400
  370 TP=DP/(1.-R)
  371 TPA=ABS(TP)
      IF(TPA-2.)380,380,372
  372 IF(TPA-20.)374,374,376
  374 TP=TP*(1.-TPA/40.)
      GO TO 380
  376 TP=10.*TP/TPA
  380 P3=P3-TP
      GO TO 140
C
  400 WRITE(6,4001)
 4001 FORMAT('1  P GREATER THAN 0.99, LAST RESULTS FOLLOW')
      GO TO 620
C
  450 ITM=2
      IF(DPA-XDPA)359,359,550
C
  500 IF(DPA/XDPA-.3)510,530,530
  510 IF(DPA-XDPA)359,359,520
  520 DP=XDP
      DPA=XDPA
      P3=XP3
      R=XR
      GO TO 360
  530 IF(DPA-XDPA)540,540,550
  540 XP=P3+DP/(DP-XDP)*(XP3-P3)
      XP3=P3
      XDP=DP
      XDPA=DPA
      GO TO 560
  550 XP=XP3+XDP/(XDP-DP)*(P3-XP3)
  560 IF(XP-XP3)570,590,580
  570 IF(XP-.9*XP3) 572,590,590
  572 XP= .5*XP3
      GO TO 590
  580 IF(XP-1.2*XP3) 590,590,582
  582 XP=1.2*XP3
  590 P3=XP
      IF(P.GT.0.99.AND.KOUNT.GT.12)  GO TO 400
      GO TO 140
C
  600 WRITE(6,6001)
 6001 FORMAT('1  KTOP EXCEEDED, LAST RESULTS FOLLOW')
C
  620 CALL OUT
      IF(IFR)660,660,640
  640 WRITE(6,6401)
 6401 FORMAT(1H1)
  660 GO TO(104,107,112),KTYPE
      END
C
C
C
C     ******************************************************************
      FUNCTION AL(DIA1,DIA2)
C           AL IS LENGTH OF STANDARD REDUCER FOR TWO DIAMETERS IN FEET
C
      IF(ABS(DIA1-DIA2)-.01)102,102,105
  102 AL=0.
      GO TO 118
  105 D=AMAX1(DIA1,DIA2)
      N6D=IFIX(12.*D+.9)-7
      IF(N6D)106,106,114
  106 AL=.458
      GO TO 118
  107 GO TO(108,108,109,109,110,110,111,111,112,112,113),N6D
  108 AL=.5
      GO TO 118
  109 AL=.583
      GO TO 118
  110 AL=.667
      GO TO 118
  111 AL=1.083
      GO TO 118
  112 AL=1.17
      GO TO 118
  113 AL=1.25
      GO TO 118
  114 IF(N6D-12)107,115,115
  115 AL=1.67
  118 RETURN
      END
C
C
C
C     ******************************************************************
      SUBROUTINE COEFF
      COMMON AIT3,AKL,ALPHA,AV,A3,A9,A10,A11,A15,A16,A18,A19,A24,A25,
     1  AEL2,AEL9,ANGC,ANGE, C,CN,CS,CSN,CSR,CSNR,C1,C5,C6,C7,C8,C9,C10,
     2  C12,CN1,CN5,CN6,CN7,CN8,CN9,CN10,CN12,CS1,CS5,CS6,CS7,CS8,CS9,
     3  CS10,CS12,CSN1,CSN5,CSN6,CSN7,CSN8,CSN9,CSN10,CSN12, DP,DP1,DP2,
     4  DPDL,D2,D6,D9, E,ELK,ELR,F21,F22,H,HD,HH,HH5,HLD,HTEST,HU,
     5  IPR,I1,JPR,KE,KL,KLN,KP,KTOP,KTYPE, NSD,NSH,NSH5,NSU, PAMB,
     6  PEXTRA,PTOL,P13,P15,P19, P0,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P12,
     7  QW,R,STPSZ,T,TC, UM2,UM6,UM9,USDOWN,USUP,UW2,UW6,UW9,VDIF,
     8  XIDOWN,XIUP,XKL2,XKL6,XKL9,XN2,XNN2, Y0,Y1,Y2,Y5,Y6,Y7,Y8,Y9,
     9  Y10,Y12, A31,AEL6,D12,KOUNT
     1  ,IFRST
      REAL KL,KLN
      IF(IFRST.NE.15)  GO TO 10
      IFRST=0
      P12= PAMB
   10 GO TO (100,200,300),KTYPE
  100 A50=A11-A10+A18+1.5
      PIN=P3
      POUT = P12
      GO TO 250
  200 A50=A11-A10-A25+1.5
      PIN=P5
      POUT=P12
  250 A51=A15+A16+3.
      WT=A50*D6*D6+A51*D9*D9
      WTD=D6*D6*A50/WT
      WTU=D9*D9*A51/WT
      PBOT=PIN+A50/(1.+34.*Y0/(PIN+A50/2.))
      UAV=UW6*WTD+UW9*WTU
      YAV=17.*Y0*((1./PIN+1./PBOT)*WTD+(1./PBOT+1./POUT)*WTU)
      GO TO 500
  300 UAV=UW9
      YAV=17.*Y0*(1./P9+1./P12)
C
  500 U=AMIN1(UAV,2.2)
      KL=7.70[illegible]-4*EXP(.0963*U+(-10.2908+4.3516*U)*YAV)
      KLN=.9[illegible]
      RETURN
      END
C
C

C
C     ******************************************************************
      FUNCTION DPD(X,Y)
C         DPD IS 2-PHASE DPRESS (POS.) FOR DOWNWARD VERTICAL FLOW
C         X IS STEP DISTANCE, Y IS A/W AT START OF STEP
C
      DPD=X*(1./(1.+Y)-.0227)
      RETURN
      END
C
C
C
C     ******************************************************************
      SUBROUTINE ENTR
C         THIS MAKES CALCULATIONS FOR THE ZONE BETWEEN ASPIRATOR OR
C         DIFFUSER INLET AND START OF DOWN-LEG (STATION 3 TO 6)
C
      COMMON AIT3,AKL,ALPHA,AV,A3,A9,A10,A11,A15,A16,A18,A19,A24,A25,
     1  AEL2,AEL9,ANGC,ANGE, C,CN,CS,CSN,CSR,CSNR,C1,C5,C6,C7,C8,C9,C10,
     2  C12,CN1,CN5,CN6,CN7,CN8,CN9,CN10,CN12,CS1,CS5,CS6,CS7,CS8,CS9,
     3  CS10,CS12,CSN1,CSN5,CSN6,CSN7,CSN8,CSN9,CSN10,CSN12, DP,DP1,DP2,
     4  DPDL,D2,D6,D9, E,ELK,ELR,F21,F22,H,HD,HH,HH5,HLD,HTEST,HU,
     5  IPR,I1,JPR,KE,KL,KLN,KP,KTOP,KTYPE, NSD,NSH,NSH5,NSU, PAMB,
     6  PEXTRA,PTOL,P13,P15,P19, P0,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P12,
     7  QW,R,STPSZ,T,TC, UM2,UM6,UM9,USDOWN,USUP,UW2,UW6,UW9,VDIF,
     8  XIDOWN,XIUP,XKL2,XKL6,XKL9,XN2,XNN2, Y0,Y1,Y2,Y5,Y6,Y7,Y8,Y9,
     9  Y10,Y12, A31,AEL6,D12,KOUNT
     1  ,IFRST
      COMMON/PASSX/IPASS,IERR
C
      CN1=CSNR*.78*PAMB/34.
      IPASS=0
      GO TO(100,200,300),KTYPE
  100 Y3=Y0*34./P3
      IF(KE)120,104,120
  104 IF(P3-PAMB+PEXTRA)108,108,110
  108 E=1.
      C5=C1
      CN5=CN1
      P4=P3
      P5=P3
      GO TO 138
  110 E=SQRT(1+64.348/UM2/UM2*(P3-PAMB+PEXTRA))
      P4=PAMB-PEXTRA
      GO TO 130
  120 P4=P3-(E*E-1)*UM2*UM2/64.348
      IF(P4)122,130,130
  122 P4=.01
  130 UTH= E*UM2
      DELP=.004*Y0**.6*UTH**2.6+.0026*UTH*UTH
      P5=P3-DELP
      IF(P5-20.)131,132,132
  131 IF(IPASS.GT.0)  GO TO 150
      P3 = P3 + 20. - P5
      IPASS = IPASS + 1
      WRITE(6,1311)P5
 1311 FORMAT(' '/'   P5= ',F7.2,' , SET EQUAL TO 20')
      GO TO 100
  150 IERR=1
      WRITE(6,151) P5,DELP,E,UTH,Y0
  151 FORMAT('1'/5X,'P5 TOO LOW *** CASE NOT RUN'/5X,'P5 = ',F7.2,' DELP
     1 = ',F7.2,' E = ',F7.2,' UTH = ',F7.2,' Y0 = ',F7.2 )
      GO TO 199
  132 PM=.75*P5+.25*P4
      YM=Y0*34./PM
      CS=CSR*PM/34.
      CSN=CSNR*PM*.7807/34.
C          UNITS ARE: VDIF(FT3), D2(FT),AKL(SEC-1), Y0(FRACTION),
C          UM2(FT/SEC), QW(GPM)
      VDIF=1.0472*D2**3/8./TAN(ANGE/2.)*(1.-1./SQRT(E))*(1.+1./SQRT(E)+
     A1./E)
      AKL=.161*Y0*(UM2/12./D2)**1.25*E**2.625*1.024**(TC-20.)
      C5=CS-(CS-C1)/EXP(AKL*VDIF*448.8/QW)
      IF(C5-C1-2.)135,135,134
  134 WRITE(6,1341)C5
 1341 FORMAT('1   C5-C1 GREATER THAN 2, C5= ',F12.4)
      C5=C1+2.+.2*(C5-C1-2.)
  135 CN5=CN1+(C5-C1)*(CSN-CN1)/(CS-C1)
C
  138 P2=P5
      RHO=1292.8*P2/34.0*492./(T+459.7)
      Y2=(Y0*34./P5-(C5-C1+CN5-CN1)/RHO)*UM2*(1.+Y0)/(UM2*(1.+Y0)-USDOWN
     1)
      CS=CSR*P5/34.
      CSN=CSNR*.78*P5/34.
      CS5=CS
      CSN5=CSN
      Y5=Y2
      C=C5
      CN=CN5
      XN2=8.70*Y0-(C5-C1)/32.
      XNN2=32.45*Y0-(CN5-CN1)/28.014
      AV=Y2/(1.+Y2)*XIDOWN
      IF(HH5-.01)1381,1381,1382
 1381 H=.01
      GO TO 139
 1382 H=HH5
  139 DO 140 J=1,NSH5
  140 CALL STEP(7)
C
      UM2=UM2*(1.+Y2)
      HLD=ELK*UM2*UM2/64.348-AEL2/(1.+Y2)
      PM=P2-HLD/2.
      CS=CS*PM/P2
      CSN=CSN*PM/P2
      CALL STEP(8)
C
  141 UM2=UM2*(1.+Y2)
      IF(IFIX(A3+.05))144,144,142
  142 P6=P2-.04*UM2*UM2/64.348+DPD(A3,Y2)
      H=A3/2.
      HLD=(P6-P2)/2.
      CALL STEP(9)
      CALL STEP(9)
  144 C6=C
      CN6=CN
      CS6=CS
      CSN6=CSN
      Y6=Y2
      P6=P2
  199 RETURN
C
  200 CS=CSR*P5/34.
      CS5=CS
      CSN=CSNR*.78*P5/34.
      CSN5=CSN
      C5=C1+11.8*Y0**.5/(A9+A15+A16+4.) + (CS-C1)*(1.-EXP(-.22*Y0*UW2**.
     A25/(12.*C2)**1.35))
      C=C5
      CN5=CN1+(C5-C1)*(CSN-CN1)/(CS-C1)
      CN=CN5
      P2=P5
      RHO=1292.8*P2/34.0*492./(T+459.7)
      Y2=(Y0*34./P5-(C5-C1+CN5-CN1)/RHO)*UW2*(1.+Y0)/(UW2*(1.+Y0)-USDOWN
     A)
      Y5=Y2
      XN2=8.70*Y0-(C5-C1)/32.
      XNN2=32.45*Y0-(CN5-CN1)/28.014
      AV=Y2/(1.+Y2)*XIDOWN
      GO TO 141
C
  300 P2=P9
      Y2=Y0*34./P9
      Y2=Y2*(1.+Y2)*UW9/(UW9*(1.+Y2)+USUP)
      Y9=Y2
      AV=Y2/(1.+Y2)*XIUP
      XN2=8.7*Y0
      XNN2=32.45*Y0
      C=C1
      C9=C1
      C5=C1
      CN=CN1
      CN9=CN1
      CS=CSR*P9/34.
      CS9=CS
      CSN=CSNR*.78*P9/34.
      CSN9=CSN
      GO TO 199
      END
C
C
C
C     ******************************************************************
      SUBROUTINE  HERSHY
C         THIS SUBROUTINE CALCULATES -DP/DL FOR AIR-WATER UPWARD
C           VERTICAL FLOW
C
      COMMON A1T3,AKL,ALPHA,AV,A3,A9,A10,A11,A15,A16,A18,A19,A24,A25,
     1  AEL2,AEL9,ANGC,ANGF, C,CN,CS,CSN,CSR,CSNR,C1,C5,C6,C7,C8,C9,C10,
     2  C12,CN1,CN5,CN6,CN7,CN8,CN9,CN10,CN12,CS1,CS5,CS6,CS7,CS8,CS9,
     3  CS10,CS12,CSN1,CSN5,CSN6,CSN7,CSN8,CSN9,CSN10,CSN12, DP,DP1,DP2,
     4  DPDL,D2,D6,D9, E,ELK,ELR,F21,F22,H,HD,HH,HH5,HLD,HTEST,HU,
     5  IPR,I1,JPR,KE,KL,KLN,KP,KTOP,KTYPE, NSD,NSH,NSH5,NSU, PAMB,
     6  PEXTRA,PTOL,P13,P15,P19, P0,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P12,
     7  QW,R,STPSZ,T,TC, UM2,UM6,UM9,USDOWN,USUP,UW2,UW6,UW9,VDIF,
     8  XIDOWN,XIUP,XKL2,XKL6,XKL9,XN2,XNN2, Y0,Y1,Y2,Y5,Y6,Y7,Y8,Y9,
     9  Y10,Y12, A31,AEL6,D12,KOUNT
     1  ,IFRST
      B1=3.5/D9**2.073/32.174**.415
      Y=Y1
      XP=0.91*Y
  100 TOP=B1*(QW*(Y-XP)/448.8)**.83-XP
      BOT=0.83*B1*(QW/448.8)**.83/(Y-XP)**.17+1.
      XP1=XP+TOP/BOT
      TEST=ABS(XP1-XP)
      XP=XP1
      IF(TEST-HTEST)110,110,100
  110 UM=UM9
      F=.048/(D9*UM9*62.25*1490.)**.13
      DPDL=(1.+2.*F*UM9*UM9/32.174/D9)/(1.+XP)
      RETURN
      END
C
C
C
C     ******************************************************************
      FUNCTION HL(X,D,U)
C         HL IS 1-PHASE HEAD LOSS FOR RE APPROX 100,000 TO 10,000,000
C         X AND D IN FT, U IN FT/SEC
C
      IF(X-.1)100,110,110
  100 X=.1
  110 RE=62.25*1490.*U*D
  120 IF(RE-.7E6)130,200,200
  130 HL=.00448/16.087*X/D*U*U/(RE/3.5E5)**.1510
  140 GO TO 250
  200 HL=.00356/16.087*X/D*U*U/(RE/2.E6)**.1144
  250 RETURN
      END
C
```

```
      ****************************************************************
      SUBROUTINE INTRO
          THIS MAKES CALCULATIONS FOR INITIAL GEOMETRY PLUS 1-PHASE ZONE

      COMMON AIT3,AKL,ALPHA,AV,A3,A9,A10,A11,A15,A16,A18,A19,A24,A25,
     1  AEL2,AEL9,ANGC,ANGE, C,CN,CS,CSN,CSR,CSNR,C1,C5,C6,C7,C8,C9,C10,
     2  C12,CN1,CN5,CN6,CN7,CN8,CN9,CN10,CN12,CS1,CS5,CS6,CS7,CS8,CS9,
     3  CS10,CS12,CSN1,CSN5,CSN6,CSN7,CSN8,CSN9,CSN10,CSN12, DP,DP1,DP2,
     4  DPDL,D2,D6,D9, F,ELK,ELR,F21,F22,H,HD,HH,HH5,HLD,HTEST,HU,
     5  IPR,I1,JPR,KF,KL,KLN,KP,KTOP,KTYPE, NSD,NSH,NSH5,NSU, PAMB,
     6  PEXTRA,PTOL,P13,P15,P19, P0,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P12,
     7  OW,R,STPSZ,T,TC, UM2,UM6,UM9,USDOWN,USUP,UW2,UW6,UW9,VDIF,
     8  XIDOWN,XIUP,XKL2,XKL6,XKL9,XN2,XNN2, Y0,Y1,Y2,Y5,Y6,Y7,Y8,Y9,
     9  Y10,Y12, A31,AEL6,D12,KOUNT
     1  ,IFRST
      UW=CW*4./3.1416/448.8
      UW2=UW/D2/D2
      UW9=UW/D9/D9
      AEL2=ELR*IFIX(12.*D2+.8)/12.
      AEL6=ELR*IFIX(12.*D6+.9)/12.
      AEL9=ELR*IFIX(12.*D9+.8)/12.
      IF(A16-.1)80,80,90
   80 A15=A11-A10-A19-AEL9-D9/2.-.5
      GO TO 95
   90 A15=A11-A10-A19-2.*AEL9-D9/2.-.5
   95 IF(KTYPE-2)100,100,300
  100 UW6=UW/D6/D6
      A3=AL(D2,D6)
      A31=AL(D6,D9)
      IF(KTYPE-1)500,120,200
  120 IF(A18-.05)130,140,140
  130 A24=0.
      P13=0.
      GO TO 150
  140 A24=A18+2.12*D2
      A1T3=A24/.707+F22*D2
      P13=A18+HL(A1T3,D2,UW2)+.4*UW2*UW2/64.348
  150 P3=PAMB+5.
      A9=A11-.5-D9/2.-AEL9-A31-A3-AEL2-A10+A18
      GO TO 500

  200 A9=A11-.5-D9/2.-AEL9-A31-A3-A25-AEL2-A10
      IF(A9-8.)210,220,220
  210 D6=D2
      A9=A9+2.*A3
      A3=0.
  220 P15=ELK*UW2*UW2/64.348+HL(A25,D2,UW2)-A25-AEL2
      P5=PAMB+5.-P15
      GO TO 500
C
  300 IF(KP)320,310,320
  310 A9=A11-A10-AEL2-AEL9-D9/2.-.5
      P19=ELK/64.348*(UW2*UW2+2.*UW9*UW9) +HL(A9,D2,UW2)-A9-AEL2
      P9=PAMB+5.-P19
      GO TO 500
  320 A9=0.
  500 IF(JPR)510,520,510
  510 WRITE(6,5001)UW2,UW9,D2,D6,D9,A3,A9,A15,A16
 5001 FORMAT('1  UW2,UW9,D2,D6,D9,A3,A9,A15,A16'/9E12.5)
  520 RETURN
      END
C
C
C
C     ****************************************************************
      SUBROUTINE OUT
C
      COMMON AIT3,AKL,ALPHA,AV,A3,A9,A10,A11,A15,A16,A18,A19,A24,A25,
     1  AEL2,AEL9,ANGC,ANGE, C,CN,CS,CSN,CSR,CSNR,C1,C5,C6,C7,C8,C9,C10,
     2  C12,CN1,CN5,CN6,CN7,CN8,CN9,CN10,CN12,CS1,CS5,CS6,CS7,CS8,CS9,
     3  CS10,CS12,CSN1,CSN5,CSN6,CSN7,CSN8,CSN9,CSN10,CSN12, DP,DP1,DP2,
     4  DPDL,D2,D6,D9, F,ELK,ELR,F21,F22,H,HD,HH,HH5,HLD,HTEST,HU,
     5  IPR,I1,JPR,KF,KL,KLN,KP,KTOP,KTYPE, NSD,NSH,NSH5,NSU, PAMB,
     6  PEXTRA,PTOL,P13,P15,P19, P0,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P12,
     7  OW,R,STPSZ,T,TC, UM2,UM6,UM9,USDOWN,USUP,UW2,UW6,UW9,VDIF,
     8  XIDOWN,XIUP,XKL2,XKL6,XKL9,XN2,XNN2, Y0,Y1,Y2,Y5,Y6,Y7,Y8,Y9,
     9  Y10,Y12, A31,AEL6,D12,KOUNT
     1  ,IFRST
      REAL KL,KLN
      A21=F21*D2
      A22=F22*D2
      D2P=12.*D2
      D6P=12.*D6
      D9P=12.*D9
      Y0P=100.*Y0
      Y5P=100.*Y5
      Y6P=100.*Y6
      Y7P=100.*Y7
      Y8P=100.*Y8
      Y9P=100.*Y9
      Y10P=100.*Y10
      Y12P=100.*Y12
      WC=2.88*Y0P
      IF(KTYPE-2)90,160,160
   90 PO=P3+P13
      F=P*100.
      IF(F-.01)100,100,110
  100 A23=0.
      GO TO 120
  110 F23=.3
      A23=D2*(1.-1./SQRT(F))/2.*(1./TAN(ANGE/2.)+1./TAN(ANGE/2.))+F23*D2
  120 A20=A24+A22+A23+A21+AEL2+3.*AEL9+A16
      S1=A24/.707+A22+A21
      S2=A15+A16
      DP1=HL(S1,D2,UW2)+UW2*UW2/64.348*(.17*(F*E-1.)+.4+ELK+.04)+HL(A9,
     1 D6,UW6)+UW9*UW9/64.348*(.04+3.*ELK)+HL(S2,D9,UW9) -A19
      IF(A16-.05)152,300,300
  152 DP1=DP1-UW9*UW9/64.348*ELK
      GO TO 300
C
  160 A18=0.
      A21=0.
      A22=0.
      P4=.01
      F=1.
      R=0.
      P2=P1
      C3=C1
      CN2=CN1
      IF(KTYPE-2)170,170,180
  170 PO=P5+P15
      A20=AEL2+2.*AEL9+A16
      S2=A15+A16
      DP1 = UW2*UW2/62.348*(ELK+.04) +  HL(A25,D2,UW2) + HL(A9,D6,UW6)
     1+ UW9*UW9/64.348*(3.*ELK+.04) + HL(S2,D9,UW9)
      IF(A16-.05)172,174,174
  172 DP1 = DP1 - UW9*UW9/62.348*ELK
  174 DP1 = DP1 - A19
      GO TO 200
  180 D6P=D2P
      P5=.01
      P6=.01
      P7=.01
      P8=.01
      C5=C1
      C6=C1
      C7=C1
      C8=C1
      CN5=CN1
      CN6=CN1
      CN7=CN1
      CN8=CN1
      CS5=.01
      CS6=.01
      CS7=.01
      CS8=.01
      CSN5=.01
      CSN6=.01
      CSN7=.01
      CSN8=.01
      Y5P=.01
      Y6P=.01
      Y7P=.01
      Y8P=.01
      PO=P9+P19
      S2=A15+A16
      IF(KP)190,200,190
  190 A20=.01
      PO=.01
      P3=.01
      A9=.01
      DP1=A19+AEL9+HL(S2,D9,UW9)+UW9*UW9/64.348*ELK
      GO TO 200
  200 A20=AEL2+3.*AEL9+A16
      DP1=UW2*UW2/64.348*(ELK+.08)+HL(A9,D2,UW2)+UW9*UW9/64.348*(3.*ELK)
     1 +HL(S2,D9,UW9)-A19
```

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```
      IF(A16-.05)210,210,300
  210 DP1=DP1-UW9*UW9/64.348*ELK
C
  300 CONTINUE
      X2=KL*1.E4
      X6=KL*1.E4
      X9=KL*1.E4
      DP2=P0-P12
C
      WRITE(6,1001)
 1001 FORMAT(1H1,///)
      WRITE(6,1002)KTYPE,A11,YCP,A25,WC,D2P, QW,D6P, E,D9P
 1002 FORMAT(T14,'KTYPE',T44,I1, T61,'A11 (CP. TO CASING BOT.)',T92,F6.2
     1/  T14,'INIT. A/W AT 68F,1ATM (O/O)',T43,F5.2,  T61,'A25 (STR. DRO
     2P TO DIFFUSER)',T92,F6.2/  T14,'OXYGEN SUPPLIED (MG/L)', T42,F5.1,
     3 T61,'EXIST. PIPE I.D.(INCH)',T92,F7.3/  T14,'WATER FLOWRATE (GPM)
     4',T39,F7.0, T61,'DOWN PIPE I.D.(INCH)',T92,F7.3/  T14,'VENTURI CON
     5TRACTION RATIO',T43,F5.2,  T61,'UP PIPE I.D.(INCH)', T92,F7.3/)
C
      WRITE(6,1003)PAMB,T,A9,UW2,A10,UW9,A15,P4,A16,R,A18,ELK
 1003 FORMAT(T14,'AMBIENT PRESS.(FT H2O)',T43,F4.1,  T61,'TEMPERATURE (F
     1)',T92,F5.1/   T14,'A9 (DOWN-LEG LENGTH, FT)',T42,F6.2,  T61,'SUPE
     2RFICIAL UW IN (FT/SEC)',T93,F5.2/ T14,'A10 (GRADE TO EXIST. C-L)',
     3 T42,F6.2,  T61,'SUPERFICIAL UW UP (FT/SEC)', T93,F5.2/   T14,'A15
     4 (UP-LEG LENGTH)', T42,F6.2, T61,'SUPF. THROAT PRESS.(FT H2O)', T9
     53,F5.2/   T14,'A16 (EXIT HORIZONTAL)', T42,F6.2, T61,'V. PERM. DP/
     6THROAT DP (O/O)',T93,F5.1/  T14,'A18 (RISE TO ASPIRATOR C-L)',
     7T43,F5.2,  T61,'ELBOW LOSS COEFFICIENT',T94,F4.2)
C
      WRITE(6,1013)A19,FLR, A20,USDOWN, A21,USUP, A22,XIDOWN, DP1,XIUP,
     1DP2
 1013 FORMAT(T14,'A19 (DROP TO OUTLET C-L)', T42,F6.2, T61,'ELBOW CL-TO-
     1FACE/DIA.', T94,F3.1/   T14,'A20 (OVERALL HORIZONTAL)', T42,F6.2,
     2T61,'SLIP VELOCITY DOWN (FT/SEC)',T94,F3.1/  T14,'A21 (SPOOL AT AS
     3P. EXIT)', T42,F6.2, T61,'SLIP VELOCITY UP (FT/SEC)',T94,F3.1/
     4T14,'A22 (SPOOL AT ASP. ENTR.)', T42,F6.2, T61,'XI DOWN (1/FT)',
     5T91,F5.0/   T14,'1-PHASE DP (FT H2O)', T42,F6.2, T61,'XI UP (1/FT)
     6',T91,F5.0/ T14,'2-PHASE DP (FT H2O)', T42,F6.2//)
C
      WRITE(6,1004)
 1004 FORMAT(T6,'STATION',T23,'1', T33,'3',T43,'5', T53,'6',T63,'7', T73
     1,'8',T93,'9', T93, '10',T102,'12'//T6,'LOCATION',T20,'ENTRANCE', T
     230,'ASP. IN',  T40,'2-PHASE', T50, 'LEG TOP', T60, 'LEG BOT.',
     3T70,'BEND IN', T80,'BEND OUT', T90,'LEG TOP', T101,'EXIT'/)
C
      WRITE(6,1005)C1,C1,C5,C6,C7,C8,C9,C10,C12,  CN1,CN1,CN5,CN6,CN7,
     1CN8,CN9,CN10,CN12,  P0,P3,P5,P6,P7,P8,P9,P10,P12
 1005 FORMAT(5X,'D.O.(MG/L)',4X,9(F5.2,5X)//5X, 'D.N.(MG/L)',4X, 9(F5.2,
     15X)//5X, 'P (FT H2O)',3X, 9(F6.2,4X)/)
C
      WRITE(6,1006)CS5,CS6,CS7,CS8,CS9,CS10,CS12,CSN5,CSN6,CSN7,CSN8,
     1CSN9,CSN10,CSN12, Y5P,Y6P,Y7P,Y8P,Y9P,Y10P,Y12P, ALPHA,
     2X2,X6,X6,X9,X9,X9,X9
 1006 FORMAT(5X, 'SAT. D.O.', 25X,7(F5.2,5X)//
     A5X, 'SAT. D.N.', 24X,7(F6.2,4X)//
     B5X, 'A/W (O/O)', 25X,7(F5.2,5X)//
     C5X, 'KL*E4, INCL. ALPHA=',F4.2,  ' (FPS)', 4X,7(F6.2,4X))
      RETURN
      END
C
C
C
C     ******************************************************************
      SUBROUTINE STEP(LEG)
C
C         THIS SUBROUTINE MAKES CALCULATIONS FOR ONE LENGTH INCREMENT
C                 LEG=1 FOR DOWN-LEG (STATION 6-7)
C                 LEG=2 FOR UP-LEG (ST.9-10)
C                 LEG=3 FOR BOTTOM REDUCER (ST.7-8)
C                 LEG=4 FOR RETURN BEND (ST.8-9)
C                 LEG=5 FOR EXIT ELBOW (ST. 10-11)
C                 LEG=6 FOR HORIZONTAL EXIT PIPE (ST. 11-12)
C                 LEG=7 FOR HORIZONTAL ENTRANCE PIPE (FROM ST. 5)
C                 LEG=8 FOR ENTRANCE ELBOW
C                 LEG=9 FOR ENTRANCE REDUCER (TO ST. 6)
C
      COMMON AIT3,AKL,ALPHA,AV,A3,A9,A10,A11,A15,A16,A18,A19,A24,A25,
     1  AEL2,AEL9,ANGC,ANGF, C,CN,CS,CSN,CSR,CSNR,C1,C5,C6,C7,C8,C9,C10,
     2  C12,CN1,CN5,CN6,CN7,CN8,CN9,CN10,CN12,CS1,CS5,CS6,CS7,CS8,CS9,
     3  CS10,CS12,CSN1,CSN5,CSN6,CSN7,CSN8,CSN9,CSN10,CSN12, DP,DP1,DP2,
     4  DPDL,D2,D6,D9, F,ELK,ELR,F21,F22,H,HD,HH,HH5,HLD,HTEST,HU,
     5  IPP,I1,JPP,KE,KL,KLN,KP,KTOP,KTYPE, NSD,NSH,NSH5,NSU, PAMB,
     6  PEXTRA,PTOL,P13,P15,P19, P0,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P12,
     7  QW,R,STPSZ,T,TC, UM2,UM6,UM9,USDOWN,USUP,UW2,UW6,UW9,VDIF,
     8 XIDOWN,XIUP,XKL2,XKL6,XKL9,XN2,XNN2, Y0,Y1,Y2,Y5,Y6,Y7,Y8,Y9,
     9 Y10,Y12, A31,AEL6,D12,KOUNT
     1 ,IFRST
      REAL KL,KLN
      P1=P2
      XN1=XN2
      XNN1=XNN2
      Y1=Y2
      UM2=UM2*(1.+Y1)
      UM6=UM6*(1.+Y1)
      UM9=UM9*(1.+Y1)
      GO TO(120,140,160,170,180,190,200,210,220),LEG
  120 DTA=H/(UM6-USDOWN)
      DTW=H/UM6
      P2=P1+DPD(H,Y1)
      GO TO 230
  140 DTA=H/(UM9+USUP)
      DTW=H/UM9
      CALL HERSHY
      P2=P1-DPDL*H
      GO TO 230
  160 UMR=(UM6+UM9)/2.
      DTA=H/(UMR-USDOWN)
      DTW=H/UMR
      P2=P1+HLD
      GO TO 230
  170 DTW=1.5708*AEL9/UM2
      DTA=DTW
      P2=P1-HLD
      GO TO 230
  180 DTW=.7854*AEL9/UM9
      DTA=DTW
      P2=P1-HLD
      GO TO 230
  190 DTW=H/UM9
      DTA=DTW
      P2=P1-HL(H,D9,UM9)
      GO TO 230
  200 DTW=H/UM2
      DTA=DTW
      P2=P1-HL(H,D2,UM2)
      GO TO 230
  210 DTW=.7854*AEL2/UM2
      DTA=DTW
      P2=P1-HLD
      GO TO 230
  220 UMR=(UM2+UM6)/2.
      DTW=H/UMR
      DTA=H/(UMR-USDOWN)
      P2=P1+HLD
  230 DC=KL*AV*(CS-C)*DTW
      DCN=KLN*AV*(CSN- CN)*DTW
      C=C+DC
      CN=CN+DCN
      XN2=XN1-DC/32.*DTA/DTW
      XNN2=XNN1-DCN/28.014*DTA/DTW
      XNT=XN2+XNN2+0.4235*Y0
      PO =XN2/XNT*(P2-.78)
      PN =XNN2/XNT*(P2-0.78)
      CS=CSR*PO/7.122
      CSN=CSNR*PN/34.
      RHO=1292.8*P2/34.0*492./(T+459.7)
      Y2 = P1/P2*Y1-(DC+DCN)/RHO
      GO TO(240,250,240,260,270,250,240,240,240),LEG
  240 AV=Y2/(1.+Y2)*XIDOWN
      GO TO 300
  250 AV=Y2/(1.+Y2)*XIUP
      GO TO 300
  260 UM0=UM2*(1.+Y0)
      Y2=Y2*(UM0-USDOWN)/UM0*UM9/(UM9+USUP)
      GO TO 250
  270 Y2=Y2*(UM9+USUP)/UM9
      GO TO 250
  300 ILEG=LEG
      NAMELIST /PRJ/C,CN,CS,CSN,P1,P2,Y2,AV,KL,KLN,H,ILEG
      IF(JPR)302,302,301
  301 WRITE(6,PRJ)
  302 CONTINUE
      RETURN
      END
```

APPENDIX D

SAMPLE OUTPUT FROM U-TUBE DESIGN PROGRAM

Several typical print-outs from the U-tube design program are reproduced in this Appendix. The program was described in Section VIII and Appendix C. Most of the quantities appearing in the print-outs have been previously defined and/or are listed in the Glossary; however, the following notes may be helpful.

There are a number of physical dimensions given in the print-outs. These are defined in the U-tube schematic diagrams of Fig. 44 and 45; however, some translation is necessary because of the limitations of computer printers: the variable a_9 (shown in Fig. 44) is printed as A9. The quantities "1-PHASE DP" and "2-PHASE DP" are the net pressure differences between the entrance (station 1) and exit (station 12) with water flow only and with air-water flow, respectively. The variable "V. PERM. DP THROAT DP" is the ratio of venturi permanent pressure drop to pressure change from entrance to throat, multiplied by 100 (this is 100 times the variable R, previously defined). The values of XI are values of air-water interfacial area per unit air volume (variable X as previously defined). The nine-column table in the bottom portion of the print-out contains values for each of the printed variables at each of the nine stations listed at the top of the table (the station numbers are those given in Fig. 44 and 45). The pressures given in the lower table of each print-out are static pressures. The air-to-water volume ratios are local values, expressed at the local temperature and pressure.

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```
         KTYPE                              1              A11 (GR. TO CASING BOT.)          40.00
         INIT. A/W AT 68F,1ATM (0/0)     5.00              A25 (STR. DROP TO DIFFUSER)        0.0
         OXYGEN SUPPLIED (MG/L)          14.0              EXIST. PIPE I.D.(INCH)            23.250
         WATER FLOWRATE (GPM)           3472.              DOWN PIPE I.D.(INCH)              23.250
         VENTURI CONTRACTION RATIO       1.00              UP PIPE I.D.(INCH)                29.000

         AMBIENT PRESS.(FT H2O)          34.0              TEMPERATURE (F)                   68.0
         A9 (DOWN-LEG LENGTH, FT)        30.00             SUPERFICIAL UW IN (FT/SEC)         2.62
         A10 (GRADE TO EXIST. C-L)        0.0              SUPERFICIAL UW UP (FT/SEC)         1.69
         A15 (UP-LEG LENGTH)             26.67             SUPF. THROAT PRESS.(FT H2O)       27.80
         A16 (EXIT HORIZONTAL)            0.0              V. PERM. DP/THROAT DP (0/0)        0.0
         A18 (RISE TO ASPIRATOR C-L)      0.0              ELBOW LOSS COEFFICIENT             0.46
         A19 (DROP TO OUTLET C-L)         8.00             ELBOW CL-TO-FACE/DIA.              1.5
         A20 (OVERALL HORIZONTAL)        18.33             SLIP VELOCITY DOWN (FT/SEC)        0.2
         A21 (SPOOL AT ASP. EXIT)         1.94             SLIP VELOCITY UP (FT/SEC)          0.2
         A22 (SPOOL AT ASP. ENTR.)        1.94             XI DOWN (1/FT)                   470.
         1-PHASE DP (FT H2O)             -7.82             XI UP (1/FT)                     470.
         2-PHASE DP (FT H2O)             -6.20

STATION               1         2        5         6         7         8         9        10        12

LOCATION          ENTRANCE  ASP. IN   2-PHASE   LEG TOP   LEG BOT.  BEND IN   BEND OUT  LEG TOP     EXIT

D.O.(MG/L)          0.0       0.0       0.0       0.29      2.05      2.15      2.45      3.76      3.76

D.N.(MG/L)         15.07     15.07     15.07     14.97     15.64     15.73     15.99     16.76     16.76

P (FT H2O)         27.80     27.80     27.80     20.95     58.66     60.24     60.20     34.00     34.00

SAT. D.O.                               7.41      7.78     13.59     13.87     13.63      7.05      7.05

SAT. D.N.                              12.32     13.27     26.47     27.25     27.30     15.51     15.51

A/W (0/0)                               6.59      5.98      3.00      2.91      2.40      4.08      4.08

KL*E4, INCL. ALPHA=0.90 (FPS)           9.08      9.08      9.08      9.08      9.08      9.08      9.08
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         KTYPE                              1              A11 (GR. TO CASING BOT.)          40.00
         INIT. A/W AT 68F,1ATM (0/0)    10.00              A25 (STR. DROP TO DIFFUSER)        0.0
         OXYGEN SUPPLIED (MG/L)          28.0              EXIST. PIPE I.D.(INCH)            23.250
         WATER FLOWRATE (GPM)           3472.              DOWN PIPE I.D.(INCH)              23.250
         VENTURI CONTRACTION RATIO       1.00              UP PIPE I.D.(INCH)                29.000

         AMBIENT PRESS.(FT H2O)          34.0              TEMPERATURE (F)                   68.0
         A9 (DOWN-LEG LENGTH, FT)        30.00             SUPERFICIAL UW IN (FT/SEC)         2.62
         A10 (GRADE TO EXIST. C-L)        0.0              SUPERFICIAL UW UP (FT/SEC)         1.69
         A15 (UP-LEG LENGTH)             26.67             SUPF. THROAT PRESS.(FT H2O)       28.66
         A16 (EXIT HORIZONTAL)            0.0              V. PERM. DP/THROAT DP (0/0)        0.0
         A18 (RISE TO ASPIRATOR C-L)      0.0              ELBOW LOSS COEFFICIENT             0.46
         A19 (DROP TO OUTLET C-L)         8.00             ELBOW CL-TO-FACE/DIA.              1.5
         A20 (OVERALL HORIZONTAL)        18.33             SLIP VELOCITY DOWN (FT/SEC)        0.2
         A21 (SPOOL AT ASP. EXIT)         1.94             SLIP VELOCITY UP (FT/SEC)          0.2
         A22 (SPOOL AT ASP. ENTR.)        1.94             XI DOWN (1/FT)                   470.
         1-PHASE DP (FT H2O)             -7.82             XI UP (1/FT)                     470.
         2-PHASE DP (FT H2O)             -5.34

STATION               1         2        5         6         7         8         9        10        12

LOCATION          ENTRANCE  ASP. IN   2-PHASE   LEG TOP   LEG BOT.  BEND IN   BEND OUT  LEG TOP     EXIT

D.O.(MG/L)          0.0       0.0       0.0       0.50      3.41      3.58      4.08      5.91      5.91

D.N.(MG/L)         15.07     15.07     15.07     14.93     16.16     16.26     16.70     17.72     17.72

P (FT H2O)         28.66     28.66     28.66     21.26     58.27     59.81     59.76     34.00     34.00

SAT. D.O.                               7.64      7.99     13.62     14.12     13.93      7.45      7.45

SAT. D.N.                              12.76     13.57     26.14     26.87     26.93     15.34     15.34

A/W (0/0)                              12.75     11.65      6.65      5.88      4.89      8.36      8.36

KL*E4, INCL. ALPHA=0.90 (FPS)           8.72      8.72      8.72      8.72      8.72      8.72      8.72
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KTYPE                                  1           A11 (GR. TO CASING BOT.)          40.00
INIT. A/W AT OPF,1ATM (O/O)        15.00           A25 (STR. DROP TO DIFFUSER)        0.0
OXYGEN SUPPLIED (MG/L)             42.0            EXIST. PIPE I.D.(INCH)            23.250
WATER FLOWRATE (GPM)             3472.             DOWN PIPE I.D.(INCH)              23.250
VENTURI CONTRACTION RATIO           1.00           UP PIPE I.D.(INCH)                29.000

AMBIENT PRESS.(FT H2O)             34.0            TEMPERATURE (F)                   68.0
A9 (DOWN-LEG LENGTH, FT)           30.00           SUPERFICIAL UW IN (FT/SEC)         2.62
A10 (GRADE TO EXIST. C-L)           0.0            SUPERFICIAL UW UP (FT/SEC)         1.69
A15 (UP-LEG LENGTH)                26.67           SUPF. THROAT PRESS.(FT H2O)       29.42
A16 (EXIT HORIZONTAL)               0.0            V. PERM. DP/THROAT DP (O/O)        0.0
A18 (RISE TO ASPIRATOR C-L)         0.0            ELBOW LOSS COEFFICIENT             0.46
A19 (DROP TO OUTLET C-L)            7.00           ELBOW CL-TO-FACE/DIA.              1.5
A20 (OVERALL HORIZONTAL)           18.23           SLIP VELOCITY DOWN (FT/SEC)        0.2
A21 (SPOOL AT ASP. EXIT)            1.94           SLIP VELOCITY UP (FT/SEC)          0.2
A22 (SPOOL AT ASP. ENTR.)           1.94           XI DOWN (1/FT)                   470.
1-PHASE DP (FT H2O)                -7.82           XI UP (1/FT)                     470.
2-PHASE DP (FT H2O)                -4.57

STATION               1         3         5         6         7         8         9         10        12

LOCATION          ENTRANCE   ASP. IN   2-PHASE   LEG TOP   LEG BOT.   BEND IN   BEND OUT  LEG TOP    EXIT

D.O.(MG/L)          0.0       0.0       0.0      0.64      4.35      4.57      5.20      7.21      7.21

D.N.(MG/L)        15.07     15.07     15.07     14.91     16.46     16.66     17.24     18.27     18.27

P (FT H2O)        29.42     29.42     29.42     31.88     57.90     59.39     59.34     33.99     33.99

SAT. D.O.                             7.64      6.17     13.97     14.28     14.12      7.72      7.72

SAT. D.N.                            13.04     13.64     25.67     26.57     26.61     15.22     15.22

A/W (O/O)                            18.56     17.09      9.15      8.90      7.45     12.76     12.76

KL*E4, INCL. ALPHA=0.90 (FPS)         8.38      8.38      8.38      8.38      8.38      8.38      8.38
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KTYPE                                  1           A11 (GR. TO CASING BOT.)          40.00
INIT. A/W AT OPF,1ATM (O/O)        20.00           A25 (STR. DROP TO DIFFUSER)        0.0
OXYGEN SUPPLIED (MG/L)             56.0            EXIST. PIPE I.D.(INCH)            23.250
WATER FLOWRATE (GPM)             3472.             DOWN PIPE I.D.(INCH)              23.250
VENTURI CONTRACTION RATIO           1.94           UP PIPE I.D.(INCH)                29.000

AMBIENT PRESS.(FT H2O)             34.0            TEMPERATURE (F)                   68.0
A9 (DOWN-LEG LENGTH, FT)           30.00           SUPERFICIAL UW IN (FT/SEC)         2.62
A10 (GRADE TO EXIST. C-L)           0.0            SUPERFICIAL UW UP (FT/SEC)         1.69
A15 (UP-LEG LENGTH)                26.67           SUPF. THROAT PRESS.(FT H2O)       30.00
A16 (EXIT HORIZONTAL)               0.0            V. PERM. DP/THROAT DP (O/O)       58.2
A18 (RISE TO ASPIRATOR C-L)         0.0            ELBOW LOSS COEFFICIENT             0.46
A19 (DROP TO OUTLET C-L)            8.00           ELBOW CL-TO-FACE/DIA.              1.5
A20 (OVERALL HORIZONTAL)           19.56           SLIP VELOCITY DOWN (FT/SEC)        0.2
A21 (SPOOL AT ASP. EXIT)            1.94           SLIP VELOCITY UP (FT/SEC)          0.2
A22 (SPOOL AT ASP. ENTR.)           1.94           XI DOWN (1/FT)                   470.
1-PHASE DP (FT H2O)                -7.77           XI UP (1/FT)                     470.
2-PHASE DP (FT H2O)                -3.70

STATION               1         3         5         6         7         8         9         10        12

LOCATION          ENTRANCE   ASP. IN   2-PHASE   LEG TOP   LEG BOT.   BEND IN   BEND OUT  LEG TOP    EXIT

D.O.(MG/L)          0.0       0.0      0.01      0.76      5.02      5.28      5.99      8.03      8.03

D.N.(MG/L)        15.07     15.07     15.06     14.92     16.74     16.97     17.63     18.57     18.57

P (FT H2O)        30.30     30.30     20.12     32.46     57.55     59.00     58.95     34.00     34.00

SAT. D.O.                             8.03      6.34     14.06     14.37     14.24      7.91      7.91

SAT. D.N.                            13.35     14.09     25.64     26.31     26.34     15.14     15.14

A/W (O/O)                            24.10     22.31     12.29     11.96     10.08     17.23     17.23

KL*E4, INCL. ALPHA=0.90 (FPS)         8.06      8.06      8.06      8.06      8.06      8.06      8.06
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KTYPE                                  1        A11 (GR. TO CASING BOT.)          40.00
INIT. A/W AT 60F,1ATM (G/G)        25.00        A25 (STR. DROP TO DIFFUSER)        0.0
OXYGEN SUPPLIED (MG/L)              70.0        EXIST. PIPE I.D.(INCH)            23.250
WATER FLOWRAT. (GPM)               3472.        DOWN PIPE I.D.(INCH)              23.250
VENTURI CONTRACTION RATIO           6.56        UP PIPE I.D.(INCH)                29.000

AMBIENT PRESS.(FT H2O)              34.0        TEMPERATURE (F)                   66.0
A9 (DOWN-LEG LENGTH, FT)           30.00        SUPERFICIAL LW IN (FT/SEC)         2.62
A10 (GRADE TO EXIST. C-L)            0.0        SUPERFICIAL LW UP (FT/SEC)         1.69
A15 (UP-LEG LENGTH)                26.67        SUPF. THROAT PRESS.(FT H2O)       30.00
A16 (EXIT HORIZONTAL)                0.0        V. PERM. DP/THROAT DP (G/O)       96.5
A18 (RISE TO ASPIRATOR C-L)          0.0        ELBOW LOSS COEFFICIENT             0.46
A19 (DROP TO OUTLET C-L)            6.00        ELBOW CL-TO-FACE/DIA.              1.5
A20 (OVERALL HORIZONTAL)           21.19        SLIP VELOCITY DOWN (FT/SEC)        0.2
A21 (SPOOL AT ASP. EXIT)            1.94        SLIP VELOCITY UP (FT/SEC)          0.2
A22 (SPOOL AT ASP. ENTR.)           1.94        XI DOWN (1/FT)                   470.
1-PHASE DP (FT H2O)                -6.53        XI UP (1/FT)                     470.
2-PHASE DP (FT H2O)                 3.78

STATION              1         3         5         6         7         8         9        10        12

LOCATION       ENTRANCE   ASP. IN   2-PHASE   LEG TOP  LEG BOT.   BEND IN  BEND OUT   LEG TOP      EXIT

D.O.(MG/L)          0.0       0.0      0.42      1.21      5.75      6.02      6.79      8.69      8.69

D.N.(MG/L)        15.07     15.07     14.99     14.86     16.45     17.21     17.94     18.75     18.75

P (FT H2O)        37.77     37.77     30.73     32.97     57.21     56.21     56.56     33.99     33.99

SAT. D.O.                             8.19      8.45     14.67     14.38     14.27      8.04      8.04

SAT. D.N.                            13.82     14.33     25.44     26.19     26.11     15.08     15.08

A/W (G/G)                            29.42     27.37     15.44     15.05     12.76     21.75     21.75

KL*E4, INCL. ALPHA*C.F. (FPS)         7.96      7.96      7.96      7.96      7.96      7.96      7.96
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KTYPE                                  1        A11 (GR. TO CASING BOT.)          60.00
INIT. A/W AT 60F,1ATM (G/G)        22.00        A25 (STR. DROP TO DIFFUSER)        0.0
OXYGEN SUPPLIED (MG/L)              56.0        EXIST. PIPE I.D.(INCH)            23.250
WATER FLOWRATE (GPM)               3472.        DOWN PIPE I.D.(INCH)              23.250
VENTURI CONTRACTION RATIO           9.23        UP PIPE I.D.(INCH)                29.000

AMBIENT PRESS.(FT H2O)              34.0        TEMPERATURE (F)                   60.0
A9 (DOWN-LEG LENGTH, FT)           50.00        SUPERFICIAL LW IN (FT/SEC)         2.62
A10 (GRADE TO EXIST. C-L)            0.0        SUPERFICIAL LW UP (FT/SEC)         1.69
A15 (UP-LEG LENGTH)                46.67        SUPF. THROAT PRESS.(FT H2O)       30.00
A16 (EXIT HORIZONTAL)                0.0        V. PERM. DP/THROAT DP (G/O)       84.0
A18 (RISE TO ASPIRATOR C-L)          0.0        ELBOW LOSS COEFFICIENT             0.46
A19 (DROP TO OUTLET C-L)            8.00        ELBOW CL-TO-FACE/DIA.              1.5
A20 (OVERALL HORIZONTAL)           21.24        SLIP VELOCITY DOWN (FT/SEC)        0.2
A21 (SPOOL AT ASP. EXIT)            1.94        SLIP VELOCITY UP (FT/SEC)          0.2
A22 (SPOOL AT ASP. ENTR.)           1.94        XI DOWN (1/FT)                   470.
1-PHASE DP (FT H2O)                -6.27        XI UP (1/FT)                     470.
2-PHASE DP (FT H2O)                 5.00

STATION              1         3         5         6         7         8         9        10        12

LOCATION       ENTRANCE   ASP. IN   2-PHASE   LEG TOP   LEG BOT   BEND IN  BEND OUT   LEG TOP      EXIT

D.O.(MG/L)          0.0       0.0      0.40      1.13      7.72      7.95      8.60     10.34     10.34

D.N.(MG/L)        15.07     15.07     15.06     14.92     19.74     19.94     20.79     21.93     21.93

P (FT H2O)        39.00     39.00     31.44     33.65     76.66     76.17     76.12     34.00     34.00

SAT. D.O.                             8.06      8.64     18.16     18.46     18.33      7.69      7.69

SAT. D.N.                            13.93     14.71     34.54     35.24     35.27     15.23     15.23

A/W (G/G)                            23.06     21.46      9.01      6.02      7.41     16.78     16.78

KL*E4, INCL. ALPHA*C.F. (FPS)         8.13      8.13      8.13      8.13      8.13      8.13      8.13
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KTYPE                             2           A11 (GR. TO CASING BOT.)          20.00
INIT. A/W AT 68F,1ATM (O/O)   20.00           A25 (STR. DROP TO DIFFUSER)        0.10
OXYGEN SUPPLIED (MG/L)         56.0           EXIST. PIPE I.D.(INCH)            23.250
WATER FLOWRATE (GPM)         3472.            DOWN PIPE I.D.(INCH)              23.250
VENTURI CONTRACTION RATIO      1.00           UP PIPE I.D.(INCH)                29.000

AMBIENT PRESS.(FT H2O)         34.0           TEMPERATURE (F)                   68.0
A9 (DOWN-LEG LENGTH, FT)       10.00          SUPERFICIAL UW IN (FT/SEC)         2.62
A10 (GRADE TO EXIST. C-L)      0.0            SUPERFICIAL UW UP (FT/SEC)         1.69
A15 (UP-LEG LENGTH)            14.67          SUFF. THROAT PRESS.(FT H2O)        0.01
A16 (EXIT HORIZONTAL)          0.0            V. PERM. DP/THROAT DP (O/O)        0.0
A18 (RISE TO ASPIRATOR C-L)    0.0            ELBOW LOSS COEFFICIENT             0.46
A19 (DROP TO OUTLET C-L)       0.0            ELBOW CL-TO-FACE/DIA.              1.5
A20 (OVERALL HORIZONTAL)       13.28          SLIP VELOCITY DOWN (FT/SEC)        0.2
A21 (SPOOL AT ASP. EXIT)       0.0            SLIP VELOCITY UP (FT/SEC)          0.2
A22 (SPOOL AT ASP. ENTR.)      0.0            XI DOWN (1/FT)                   470.
1-PHASE DP (FT H2O)            0.11           XI UP (1/FT)                     470.
2-PHASE DP (FT H2O)            0.96

STATION              1          3          5         6         7          8          9         10        12

LOCATION         ENTRANCE   ASP. IN   2-PHASE   LEG TOP   LEG BOT.   BEND IN   BEND OUT   LEG TOP     EXIT

D.O.(MG/L)          0.0        0.0       0.20      0.20      1.92       2.24       2.14      5.19      5.19

D.N.(MG/L)         15.67      15.67     15.10     15.10     15.58      15.73      16.15     16.59     16.59

P (FT H2O)         34.60      34.60     37.95     37.95     46.25      47.66      47.60     34.00     34.00

SAT. D.O.                               10.12     10.12     11.76      12.09      11.94      8.24      8.24

SAT. D.N.                               16.62     16.62     20.31      20.96      20.99     14.99     14.99

A/W (O/O)                               19.11     19.11     19.55      15.06      12.74     17.62     17.62

KL*E4, INCL. ALPHA=[illegible] (FPS)    7.67      7.67      7.67       7.87       7.87      7.87      7.87
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KTYPE                             2           A11 (GR. TO CASING BOT.)          20.00
INIT. A/W AT 68F,1ATM (O/O)   40.00           A25 (STR. DROP TO DIFFUSER)        0.10
OXYGEN SUPPLIED (MG/L)        112.0           EXIST. PIPE I.D.(INCH)            23.250
WATER FLOWRATE (GPM)         3472.            DOWN PIPE I.D.(INCH)              23.250
VENTURI CONTRACTION RATIO      1.00           UP PIPE I.D.(INCH)                29.000

AMBIENT PRESS.(FT H2O)         34.0           TEMPERATURE (F)                   68.0
A9 (DOWN-LEG LENGTH, FT)       10.00          SUPERFICIAL UW IN (FT/SEC)         2.62
A10 (GRADE TO EXIST. C-L)      0.0            SUPERFICIAL UW UP (FT/SEC)         1.69
A15 (UP-LEG LENGTH)            14.67          SUFF. THROAT PRESS.(FT H2O)        0.01
A16 (EXIT HORIZONTAL)          0.0            V. PERM. DP/THROAT DP (O/O)        0.0
A18 (RISE TO ASPIRATOR C-L)    0.0            ELBOW LOSS COEFFICIENT             0.46
A19 (DROP TO OUTLET C-L)       0.0            ELBOW CL-TO-FACE/DIA.              1.5
A20 (OVERALL HORIZONTAL)       13.28          SLIP VELOCITY DOWN (FT/SEC)        0.2
A21 (SPOOL AT ASP. EXIT)       0.0            SLIP VELOCITY UP (FT/SEC)          0.2
A22 (SPOOL AT ASP. ENTR.)      0.0            XI DOWN (1/FT)                   470.
1-PHASE DP (FT H2O)            0.11           XI UP (1/FT)                     470.
2-PHASE DP (FT H2O)            1.31

STATION              1          3          5         6         7          8          9         10        12

LOCATION         ENTRANCE   ASP. IN   2-PHASE   LEG TOP   LEG BOT.   BEND IN   BEND OUT   LEG TOP     EXIT

D.O.(MG/L)          0.0        0.0       0.29      0.29      2.40       2.60       3.90      6.23      6.23

D.N.(MG/L)         15.07      15.07     15.12     15.12     15.70      15.87      16.37     16.74     16.74

P (FT H2O)         35.31      35.31     38.36     38.36     45.57      46.80      46.73     34.00     34.00

SAT. D.O.                               10.22     10.22     11.73      12.02      11.92      8.48      8.48

SAT. D.N.                               17.00     17.00     19.95      20.51      20.52     14.89     14.89

A/W (O/O)                               37.47     37.47     31.37      30.51      26.40     36.06     36.06

KL*E4, INCL. ALPHA=0.90 (FPS)           6.54      6.54      6.54       6.54       6.54      6.54      6.54
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         KTYPE                               2             A11 (GR. TO CASING BOT.)           40.00
         INIT. A/W AT 68F,1ATM (O/O)     10.00             A25 (STR. DROP TO DIFFUSER)         0.10
         OXYGEN SUPPLIED (MG/L)           28.0             EXIST. PIPE I.D.(INCH)             23.250
         WATER FLOWRATE (GPM)           3472.              DOWN PIPE I.D.(INCH)               23.250
         VENTURI CONTRACTION RATIO        1.00             UP PIPE I.D.(INCH)                 29.000

         AMBIENT PRESS.(FT H2O)           34.0             TEMPERATURE (F)                    68.0
         A9 (DOWN-LEG LENGTH, FT)         30.00            SUPERFICIAL UW IN (FT/SEC)          2.62
         A10 (GRADE TO EXIST. C-L)         0.0             SUPERFICIAL UW UP (FT/SEC)          1.69
         A15 (UP-LEG LENGTH)              34.67            SUPF. THROAT PRESS.(FT H2O)         0.01
         A16 (EXIT HORIZONTAL)             0.0             V. PERM. DP/THROAT DP (O/O)         0.0
         A18 (RISE TO ASPIRATOR C-L)       0.0             ELBOW LOSS COEFFICIENT              0.46
         A19 (DROP TO OUTLET C-L)          0.0             ELBOW CL-TO-FACE/DIA.               1.5
         A20 (OVERALL HORIZONTAL)         13.88            SLIP VELOCITY DOWN (FT/SEC)         0.2
         A21 (SPOOL AT ASP. EXIT)          0.0             SLIP VELOCITY UP (FT/SEC)           0.2
         A22 (SPOOL AT ASP. ENTR.)         0.0             XI DOWN (1/FT)                    470.
         1-PHASE DP (FT H2O)               0.14            XI UP (1/FT)                      470.
         2-PHASE DP (FT H2O)               1.68

STATION            1          3          5          6          7          8          9         10         12

LOCATION        ENTRANCE   ASP. IN    2-PHASE    LEG TOP    LEG BOT.   BEND IN   BEND OUT   LEG TOP     EXIT

D.O.(MG/L)        0.0        0.0       0.06       0.06       3.22       3.42       3.95       6.35       6.35

D.N.(MG/L)       15.07      15.07      15.08      15.08      16.83      17.01      17.50      18.86      18.86

P (FT H2O)       35.68      35.68      38.73      38.73      66.08      67.62      67.58      34.00      34.00

SAT. D.O.                              10.32      10.32      15.89      16.18      15.96       7.42       7.42

SAT. D.N.                              17.16      17.16      29.60      30.34      30.41      15.35      15.35

A/W (O/O)                               9.43       9.43       5.31       5.18       4.30       8.23       8.23

KL*E4, INCL. ALPHA=0.90 (FPS)           8.62       8.62       8.62       8.62       8.62       8.62       8.62
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         KTYPE                               2             A11 (GR. TO CASING BOT.)           40.00
         INIT. A/W AT 68F,1ATM (O/O)     20.00             A25 (STR. DROP TO DIFFUSER)         0.10
         OXYGEN SUPPLIED (MG/L)           56.0             EXIST. PIPE I.D.(INCH)             23.250
         WATER FLOWRATE (GPM)           3472.              DOWN PIPE I.D.(INCH)               23.250
         VENTURI CONTRACTION RATIO        1.00             UP PIPE I.D.(INCH)                 29.000

         AMBIENT PRESS.(FT H2O)           34.0             TEMPERATURE (F)                    68.0
         A9 (DOWN-LEG LENGTH, FT)         30.00            SUPERFICIAL UW IN (FT/SEC)          2.62
         A10 (GRADE TO EXIST. C-L)         0.0             SUPERFICIAL UW UP (FT/SEC)          1.69
         A15 (UP-LEG LENGTH)              34.67            SUPF. THROAT PRESS.(FT H2O)         0.01
         A16 (EXIT HORIZONTAL)             0.0             V. PERM. DP/THROAT DP (O/O)         0.0
         A18 (RISE TO ASPIRATOR C-L)       0.0             ELBOW LOSS COEFFICIENT              0.46
         A19 (DROP TO OUTLET C-L)          0.0             ELBOW CL-TO-FACE/DIA.               1.5
         A20 (OVERALL HORIZONTAL)         13.88            SLIP VELOCITY DOWN (FT/SEC)         0.2
         A21 (SPOOL AT ASP. EXIT)          0.0             SLIP VELOCITY UP (FT/SEC)           0.2
         A22 (SPOOL AT ASP. ENTR.)         0.0             XI DOWN (1/FT)                    470.
         1-PHASE DP (FT H2O)               0.14            XI UP (1/FT)                      470.
         2-PHASE DP (FT H2O)               2.48

STATION            1          3          5          6          7          8          9         10         12

LOCATION        ENTRANCE   ASP. IN    2-PHASE    LEG TOP    LEG BOT.   BEND IN   BEND OUT   LEG TOP     EXIT

D.O.(MG/L)        0.0        0.0       0.09       0.09       4.89       5.17       5.95       8.60       8.60

D.N.(MG/L)       15.07      15.07      15.09      15.09      17.75      18.01      18.74      19.86      19.86

P (FT H2O)       36.48      36.48      39.53      39.53      65.16      66.63      66.58      34.00      34.00

SAT. D.O.                              10.54      10.54      16.05      16.35      16.19       7.89       7.89

SAT. D.N.                              17.52      17.52      29.03      29.71      29.76      15.15      15.15

A/W (O/O)                              18.36      18.36      10.81      10.55       8.88      17.06      17.06

KL*E4, INCL. ALPHA=0.90 (FPS)           7.90       7.90       7.90       7.90       7.90       7.90       7.90
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        KTYPE                                 2                A11 (GR. TO CASING BOT.)          40.00
        INIT. A/W AT 68F,1ATM (0/0)   30.00                A25 (STR. DROP TO DIFFUSER)        0.10
        OXYGEN SUPPLIED (MG/L)         84.0                EXIST. PIPE I.D.(INCH)            23.250
        WATER FLOWRATE (GPM)         3472.                 DOWN PIPE I.D.(INCH)              23.250
        VENTURI CONTRACTION RATIO      1.00                UP PIPE I.D.(INCH)                29.000

        AMBIENT PRESS.(FT H2O)         34.0                TEMPERATURE (F)                   68.0
        A9 (DOWN-LEG LENGTH, FT)       30.00               SUPERFICIAL UW IN (FT/SEC)         2.62
        A10 (GRADE TO EXIST. C-L)      0.0                 SUPERFICIAL UW UP (FT/SEC)         1.69
        A15 (UP-LEG LENGTH)            34.67               SUPF. THROAT PRESS.(FT H2O)        0.01
        A16 (EXIT HORIZONTAL)           0.0                V. PERM. DP/THROAT DP (0/0)        0.0
        A18 (RISE TO ASPIRATOR C-L)     0.0                ELBOW LOSS COEFFICIENT             0.46
        A19 (DROP TO OUTLET C-L)        0.0                ELBOW CL-TO-FACE/DIA.              1.5
        A20 (OVERALL HORIZONTAL)       13.88               SLIP VELOCITY DOWN (FT/SEC)        0.2
        A21 (SPOOL AT ASP. EXIT)        0.0                SLIP VELOCITY UP (FT/SEC)          0.2
        A22 (SPOOL AT ASP. ENTR.)       0.0                XI DOWN (1/FT)                   470.
        1-PHASE DP (FT H2O)             0.14               XI UP (1/FT)                     470.
        2-PHASE DP (FT H2O)             3.13

STATION             1         3         5         6         7         8         9        10        12

LOCATION        ENTRANCE  ASP. IN   2-PHASE   LEG TOP   LEG BOT.  BEND IN   BEND OUT  LEG TOP    EXIT

D.O.(MG/L)        0.0       0.0       0.11      0.11      5.75      6.08      6.99      9.51      9.51

D.N.(MG/L)       15.07     15.07     15.09     15.09     18.23     18.52     19.37     20.08     20.08

P (FT H2O)       37.13     37.13     40.16     40.19     64.31     65.71     65.65     34.00     34.00

SAT. D.O.                            10.71     10.71     16.08     16.38     16.26      8.14      8.14

SAT. D.N.                            17.81     17.81     28.54     29.18     29.21     15.04     15.04

A/W (0/0)                            26.95     26.95     16.45     16.08     13.68     26.14     26.14

KL*E4, INCL. ALPHA=0.90 (FPS)         7.23      7.23      7.23      7.23      7.23      7.23      7.23
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        KTYPE                                 2                A11 (GR. TO CASING BOT.)          40.00
        INIT. A/W AT 68F,1ATM (0/0)   40.00                A25 (STR. DROP TO DIFFUSER)        0.10
        OXYGEN SUPPLIED (MG/L)        112.0                EXIST. PIPE I.D.(INCH)            23.250
        WATER FLOWRATE (GPM)         3472.                 DOWN PIPE I.D.(INCH)              23.250
        VENTURI CONTRACTION RATIO      1.00                UP PIPE I.D.(INCH)                29.000

        AMBIENT PRESS.(FT H2O)         34.0                TEMPERATURE (F)                   68.0
        A9 (DOWN-LEG LENGTH, FT)       30.00               SUPERFICIAL UW IN (FT/SEC)         2.62
        A10 (GRADE TO EXIST. C-L)      0.0                 SUPERFICIAL UW UP (FT/SEC)         1.69
        A15 (UP-LEG LENGTH)            34.67               SUPF. THROAT PRESS.(FT H2O)        0.01
        A16 (EXIT HORIZONTAL)           0.0                V. PERM. DP/THROAT DP (0/0)        0.0
        A18 (RISE TO ASPIRATOR C-L)     0.0                ELBOW LOSS COEFFICIENT             0.46
        A19 (DROP TO OUTLET C-L)        0.0                ELBOW CL-TO-FACE/DIA.              1.5
        A20 (OVERALL HORIZONTAL)       13.88               SLIP VELOCITY DOWN (FT/SEC)        0.2
        A21 (SPOOL AT ASP. EXIT)        0.0                SLIP VELOCITY UP (FT/SEC)          0.2
        A22 (SPOOL AT ASP. ENTR.)       0.0                XI DOWN (1/FT)                   470.
        1-PHASE DP (FT H2O)             0.14               XI UP (1/FT)                     470.
        2-PHASE DP (FT H2O)             3.67

STATION             1         3         5         6         7         8         9        10        12

LOCATION        ENTRANCE  ASP. IN   2-PHASE   LEG TOP   LEG BOT.  BEND IN   BEND OUT  LEG TOP    EXIT

D.O.(MG/L)        0.0       0.0       0.14      0.14      6.18      6.53      7.50      9.91      9.91

D.N.(MG/L)       15.07     15.07     15.10     15.10     18.44     18.75     19.64     20.07     20.07

P (FT H2O)       37.68     37.68     40.73     40.73     63.51     64.84     64.76     34.00     34.00

SAT. D.O.                            10.86     10.86     16.04     16.34     16.24      8.29      8.29

SAT. D.N.                            18.05     18.05     28.10     28.71     28.73     14.97     14.97

A/W (0/0)                            35.30     35.30     22.22     21.74     18.68     35.34     35.34

KL*E4, INCL. ALPHA=0.90 (FPS)         6.63      6.63      6.63      6.63      6.63      6.63      6.63
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KTYPE                             2          A11 (GR. TO CASING BOT.)          40.00
INIT. A/W AT 68F,1ATM (O/O)  50.00           A25 (STR. DROP TO DIFFUSER)        0.10
OXYGEN SUPPLIED (MG/L)       140.0           EXIST. PIPE I.D.(INCH)            23.250
WATER FLOWRATE (GPM)        3472.            DOWN PIPE I.D.(INCH)              23.250
VENTURI CONTRACTION RATIO     1.00           UP PIPE I.D.(INCH)                29.000

AMBIENT PRESS.(FT H2O)       34.0            TEMPERATURE (F)                   68.0
A9 (DOWN-LEG LENGTH, FT)     30.00           SUPERFICIAL UW IN (FT/SEC)         2.62
A10 (GRADE TO EXIST. C-L)     0.0            SUPERFICIAL UW UP (FT/SEC)         1.69
A15 (UP-LEG LENGTH)          34.67           SUPF. THROAT PRESS.(FT H2O)        0.01
A16 (EXIT HORIZONTAL)         0.0            V. PERM. DP/THROAT DP (O/O)        0.0
A18 (RISE TO ASPIRATOR C-L)   0.0            ELBOW LOSS COEFFICIENT             0.46
A19 (DROP TO OUTLET C-L)      0.0            ELBOW CL-TO-FACE/DIA.              1.5
A20 (OVERALL HORIZONTAL)     13.88           SLIP VELOCITY DOWN (FT/SEC)        0.2
A21 (SPOOL AT ASP. EXIT)      0.0            SLIP VELOCITY UP (FT/SEC)          0.2
A22 (SPOOL AT ASP. ENTR.)     0.0            XI DOWN (1/FT)                   470.
1-PHASE DP (FT H2O)           0.14           XI UP (1/FT)                     470.
2-PHASE DP (FT H2O)           4.13

STATION            1         3         5         6         7         8         9        10        12

LOCATION       ENTRANCE  ASP. IN   2-PHASE   LEG TOP   LEG BOT.  BEND IN   BEND OUT  LEG TOP     EXIT

D.O.(MG/L)       0.0       0.0       0.16      0.16      6.33      6.76      7.70     10.08     10.08

D.N.(MG/L)      15.07     15.07     15.11     15.11     18.45     18.60     19.69     19.98     19.98

P (FT H2O)      38.13     38.13     41.18     41.18     62.76     64.02     63.95     34.00     34.00

SAT. D.O.                           10.98     10.98     15.97     16.27     16.18      8.40      8.40

SAT. D.N.                           18.25     18.25     27.71     28.29     28.29     14.93     14.93

A/W (O/O)                           43.48     43.48     28.10     27.51     23.85     44.62     44.62

KL*E4, INCL. ALPHA=0.90 (FPS)        6.07      6.07      6.07      6.07      6.07      6.07      6.07
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KTYPE                             2          A11 (GR. TO CASING BOT.)          60.00
INIT. A/W AT 68F,1ATM (O/O)  20.00           A25 (STR. DROP TO DIFFUSER)        0.10
OXYGEN SUPPLIED (MG/L)       56.0            EXIST. PIPE I.D.(INCH)            23.250
WATER FLOWRATE (GPM)        3472.            DOWN PIPE I.D.(INCH)              23.250
VENTURI CONTRACTION RATIO     1.00           UP PIPE I.D.(INCH)                29.000

AMBIENT PRESS.(FT H2O)       34.0            TEMPERATURE (F)                   68.0
A9 (DOWN-LEG LENGTH, FT)     50.00           SUPERFICIAL UW IN (FT/SEC)         2.62
A10 (GRADE TO EXIST. C-L)     0.0            SUPERFICIAL UW UP (FT/SEC)         1.69
A15 (UP-LEG LENGTH)          54.67           SUPF. THROAT PRESS.(FT H2O)        0.01
A16 (EXIT HORIZONTAL)         0.0            V. PERM. DP/THROAT DP (O/O)        0.0
A18 (RISE TO ASPIRATOR C-L)   0.0            ELBOW LOSS COEFFICIENT             0.46
A19 (DROP TO OUTLET C-L)      0.0            ELBOW CL-TO-FACE/DIA.              1.5
A20 (OVERALL HORIZONTAL)     13.88           SLIP VELOCITY DOWN (FT/SEC)        0.2
A21 (SPOOL AT ASP. EXIT)      0.0            SLIP VELOCITY UP (FT/SEC)          0.2
A22 (SPOOL AT ASP. ENTR.)     0.0            XI DOWN (1/FT)                   470.
1-PHASE DP (FT H2O)           0.16           XI UP (1/FT)                     470.
2-PHASE DP (FT H2O)           3.76

STATION            1         3         5         6         7         8         9        10        12

LOCATION       ENTRANCE  ASP. IN   2-PHASE   LEG TOP   LEG BOT.  BEND IN   BEND OUT  LEG TOP     EXIT

D.O.(MG/L)       0.0       0.0       0.06      0.06      7.60      7.85      8.55     10.72     10.72

D.N.(MG/L)      15.07     15.07     15.08     15.08     20.79     21.10     21.98     23.10     23.10

P (FT H2O)      37.78     37.78     40.83     40.83     84.39     85.90     85.85     34.00     34.00

SAT. D.O.                           10.88     10.88     20.15     20.45     20.28      7.68      7.68

SAT. D.N.                           18.09     18.09     37.99     38.70     38.75     15.24     15.24

A/W (O/O)                           17.78     17.78      8.16      7.99      6.71     16.65     16.65

KL*E4, INCL. ALPHA=0.90 (FPS)        7.96      7.96      7.96      7.96      7.96      7.96      7.96
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        KTYPE                            2          A11 (GR. TO CASING BOT.)         80.00
        INIT. A/W AT 68F,1ATM (O/O)  20.00          A25 (STR. DROP TO DIFFUSER)       0.10
        OXYGEN SUPPLIED (MG/L)        56.0          EXIST. PIPE I.D.(INCH)           23.250
        WATER FLOWRATE (GPM)        3472.           DOWN PIPE I.D.(INCH)             23.250
        VENTURI CONTRACTION RATIO     1.00          UP PIPL I.D.(INCH)               29.000

        AMBIENT PRESS.(FT H2O)        34.0          TEMPERATURE (F)                  68.0
        A9 (DOWN-LEG LENGTH, FT)      70.00         SUPERFICIAL UW IN (FT/SEC)        2.62
        A10 (GRADE TO EXIST. C-L)      0.0          SUPERFICIAL UW UP (FT/SEC)        1.69
        A15 (UP-LEG LENGTH)           74.67         SUPF. THROAT PRESS.(FT H20)       0.01
        A16 (EXIT HORIZONTAL)          0.0          V. PERM. DP/THROAT DP (O/O)       0.0
        A18 (RISE TO ASPIRATOR C-L)    0.0          ELBOW LOSS COEFFICIENT            0.46
        A19 (DROP TO OUTLET C-L)       0.0          ELBOW CL-TO-FACE/DIA.             1.5
        A20 (OVERALL HORIZONTAL)      13.88         SLIP VELOCITY DOWN (FT/SEC)       0.2
        A21 (SPOOL AT ASP. EXIT)       0.0          SLIP VELOCITY UP (FT/SEC)         0.2
        A22 (SPOOL AT ASP. ENTR.)      0.0          XI DOWN (1/FT)                  470.
        1-PHASE DP (FT H20)            0.19         XI UP (1/FT)                    470.
        2-PHASE DP (FT H20)            4.91

STATION            1         3         5         6          7         8         9        10        12

LOCATION       ENTRANCE  ASP. IN   2-PHASE   LEG TOP   LEG BOT.   BEND IN  BEND OUT  LEG TOP     EXIT

D.O.(MG/L)       0.0       0.0       0.05      0.05      10.09     10.32     10.97     12.19     12.19

D.N.(MG/L)      15.07     15.07     15.06     15.06      24.25     24.59     25.56     26.03     26.03

P (FT H20)      38.91     38.91     41.96     41.95     103.82    105.35    105.30     34.00     34.00

SAT. D.O.                           11.18     11.18      24.10     24.39     24.20      7.55      7.55

SAT. D.N.                           18.59     18.59      47.12     47.05     47.91     15.29     15.29

A/W (O/O)                           17.30     17.30       6.47      6.36      5.32     16.33     16.33

KL*E4, INCL. ALPHA=0.90 (FPS)        8.02      8.02       8.02      8.02      8.02      8.02      8.02
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        KTYPE                            2          A11 (GR. TO CASING BOT.)        100.00
        INIT. A/W AT 68F,1ATM (O/O)  20.00          A25 (STR. DROP TO DIFFUSER)       0.10
        OXYGEN SUPPLIED (MG/L)        56.0          EXIST. PIPE I.D.(INCH)           23.250
        WATER FLOWRATE (GPM)        3472.           DOWN PIPE I.D.(INCH)             23.250
        VENTURI CONTRACTION RATIO     1.00          UP PIPL I.D.(INCH)               29.000

        AMBIENT PRESS.(FT H20)        34.0          TEMPERATURE (F)                  68.0
        A9 (DOWN-LEG LENGTH, FT)      90.00         SUPERFICIAL UW IN (FT/SEC)        2.62
        A10 (GRADE TO EXIST. C-L)      0.0          SUPERFICIAL UW UP (FT/SEC)        1.69
        A15 (UP-LEG LENGTH)           94.67         SUPF. THROAT PRESS.(FT H20)       0.01
        A16 (EXIT HORIZONTAL)          0.0          V. PERM. DP/THROAT DP (O/O)       0.0
        A18 (RISE TO ASPIRATOR C-L)    0.0          ELBOW LOSS COEFFICIENT            0.46
        A19 (DROP TO OUTLET C-L)       0.0          ELBOW CL-TO-FACE/DIA.             1.5
        A20 (OVERALL HORIZONTAL)      13.88         SLIP VELOCITY DOWN (FT/SEC)       0.2
        A21 (SPOOL AT ASP. EXIT)       0.0          SLIP VELOCITY UP (FT/SEC)         0.2
        A22 (SPOOL AT ASP. ENTR.)      0.0          XI DOWN (1/FT)                  470.
        1-PHASE DP (FT H20)            0.21         XI UP (1/FT)                    470.
        2-PHASE DP (FT H20)            5.92

STATION            1         3         5         6          7         8         9        10        12

LOCATION       ENTRANCE  ASP. IN   2-PHASE   LEG TOP   LEG BOT.   BEND IN  BEND OUT  LEG TOP     EXIT

D.O.(MG/L)       0.0       0.0       0.04      0.04      12.40     12.62     13.22     13.28     13.28

D.N.(MG/L)      15.07     15.07     15.08     15.08      27.93     28.29     29.30     28.67     28.67

P (FT H20)      39.92     39.92     42.97     42.97     123.38    124.93    124.88     34.00     34.00

SAT. D.O.                           11.45     11.45      27.88     28.16     27.95      7.45      7.45

SAT. D.N.                           19.04     19.04      56.40     57.14     57.20     15.33     15.33

A/W (O/O)                           16.89     16.89       5.30      5.23      4.37     16.08     16.08

KL*E4, INCL. ALPHA=0.90 (FPS)        8.06      8.06       8.06      8.06      8.06      8.06      8.06
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KTYPE                                3         A11 (GR. TO CASING BOT.)          30.00
INIT. A/W AT 68F,1ATM (O/O)      15.00         A25 (STR. DROP TO DIFFUSER)        0.0
OXYGEN SUPPLIED (MG/L)            42.0         EXIST. PIPE I.D.(INCH)            26.400
WATER FLOWRATE (GPM)            1800.          DOWN PIPE I.D.(INCH)              26.400
VENTURI CONTRACTION RATIO         1.00         UP PIPE I.D.(INCH)                13.250

AMBIENT PRESS.(FT H2O)            34.0         TEMPERATURE (F)                   82.4
A9 (DOWN-LEG LENGTH, FT)          23.28        SUPERFICIAL UW IN (FT/SEC)         5.11
A10 (GRADE TO EXIST. C-L)          3.50        SUPERFICIAL UW UP (FT/SEC)         4.19
A15 (UP-LEG LENGTH)               16.28        SUPF. THROAT PRESS.(FT H2O)        0.01
A16 (EXIT HORIZONTAL)              0.0         V. PERM. DP/THROAT DP (O/O)        0.0
A18 (RISE TO ASPIRATOR C-L)        0.0         ELBOW LOSS COEFFICIENT             0.75
A19 (DROP TO OUTLET C-L)           8.00        ELBOW CL-TO-FACE/DIA.              1.0
A20 (OVERALL HORIZONTAL)           4.50        SLIP VELOCITY DOWN (FT/SEC)        0.2
A21 (SPOOL AT ASP. EXIT)           0.0         SLIP VELOCITY UP (FT/SEC)          0.2
A22 (SPOOL AT ASP. ENTR.)          0.0         XI DOWN (1/FT)                   470.
1-PHASE DP (FT H2O)                7.12        XI UP (1/FT)                     470.
2-PHASE DP (FT H2O)               -8.36

STATION               1          3          5          6          7          8          9         10         12

LOCATION          ENTRANCE   ASP. IN    2-PHASE    LEG TOP    LEG BOT.   BEND IN    BEND OUT   LEG TOP      EXIT

D.O.(MG/L)          0.20       0.20       0.20       0.20       0.20       0.20       0.20       1.47       1.47

D.N.(MG/L)         13.43      13.43      13.43      13.43      13.43      13.43      13.43      13.75      13.75

P (FT H2O)         25.63      25.63       0.01       0.01       0.01       0.01      49.03      34.01      34.01

SAT. D.O.                                 0.01       0.01       0.01       0.01      11.37       7.53       7.53

SAT. D.N.                                 0.01       0.01       0.01       0.01      19.37      13.21      13.21

A/W (O/O)                                 0.01       0.01       0.01       0.01       9.97      14.24      14.24

KL*E4, INCL. ALPHA=0.80 (FPS)             8.76       8.76       8.76       8.76       8.76       8.76       8.76
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